COMPLEX ELECTRICAL PROPERTIES OF SHALE AS A FUNCTION OF FREQUENCY AND WATER CONTENT

by

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ABSTRACT

An experimental research program has been initiated to investigate the electrical properties of swelling shales (shales that have been exposed to water and are therefore expanding) across a wide frequency range, 5 Hz to 1.3 GHz. This range spans the spectrum of the commonly used downhole logging measurements, from the deep laterologs to the microwave dielectric tools. Three different methods of varying the sample's water content have been used: desiccator, electro-osmosis and air exposure methods. Two distinct measurement techniques have been used to span the frequency range: four-electrode setup for the low frequencies (5 Hz - 13 MHz), and open-ended coaxial probe with network analyzer at the high end (20 MHz - 1.3 GHz). The probe technique is simple to use, potentially enabling field measurements of complex permittivity to be taken, although some accuracy is sacrificed. The effects of swelling in shale are most pronounced at the lowest frequencies. This investigation discovered a phenomenon of shale; shale will generate a direct electrical current under stress that has potential for a wellbore diagnostic tool. Also, the best fluid for shale preservation was found to be Isopar M^{TM} (a mineral oil), saturated with deionized water.

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CHAPTER I

FORMULATION OF THE PROBLEM

1.1 Introduction (Adisoemarta and Morriss, 1992)

Anomalously low resistivity-log response in certain formations has been known to yield incorrect water saturation and to sometimes mask detection of hydrocarbon-bearing intervals. Shale, which is often the cause of the problem because of its clay content, may be in the form of laminations or grains, both detrital in origin. The interpretation problem is one of choosing the appropriate mixing rule based on both the distribution of the shale and the volume investigated by the logging measurement. An understanding of the electrical properties of the shale itself is an important element of the problem. For example, complex permittivity can be used in a model based on a volumetrically weighted mixing rule to interpret microwave-frequency measurements. In a shaly formation, these complex-time average models require values for the complex permittivity of the shale. High resolution dielectric logging measurements may be able to detect individual shale laminae if they are thick enough, in which case the shale's properties must be accounted for in the interpretation.

The electrical properties of massive shales are also of interest to the industry. The alteration of shales, caused by adsorption of water while drilling, is one of many contributors to the wellbore stability problem that costs the industry in the order of $ 400 -500 million annually (Bol et al., 1992). This alteration of shale problem has acquired a logging perspective due to the increasing use of measurements while drilling. The capability of taking real time and time-lapse measurements while still drilling introduces the possibility of detecting a swelling problem while something can still be done about it.

Improved interpretation in both of these cases requires an understanding of the effect of the shale's composition, texture, chemistry, and water content on tool response. In particular, the effect on electrical measurements can be quite large. The availability of tools operating over a wide range of frequencies is of possible benefit since the mechanisms

affecting the propagation of an electromagnetic wave differ with frequencies. Logging measurements at frequencies from 35 Hz to 1.1 GHz are commercially available.

It is common to speak of conductivity and electrical permittivity as the material properties affecting electromagnetic wave propagation. (Magnetic permeability is usually negligible in sedimentary formations.) These two properties are distinguished by the phase relation between stimulus and response, from a measurements point of view, with the conductivity being associated with the in-phase response and the permittivity with the quadrature response. The corresponding physical mechanisms are electronic or ionic movement for conductivity and various polarization mechanisms for permittivity. However, in a material as complex as a clay-bearing rock, this model is too simplistic since most mechanisms exhibit a frequency-dependent phase and amplitude response. For example, at very high frequencies, ionic conduction will not be able to stay in phase with the stimulus, just as electron conduction fails to stay in phase at optical frequencies. Mathematically, this generalization can be handled by representing both conductivity and permittivity as complex numbers. There are thus four electrical properties characterizing a clay-bearing rock.

Since water in the pore spaces and adsorbed to the mineral surfaces is a major influence on the electrical properties of a shale, this paper investigates the effect of changing the amount of bound water adsorbed to the clays. Shale samples with different clay compositions are placed sequentially in desiccators, each of which contains a different saturated salt solution that creates a known water activity. The shale is brought to equilibrium at each step, and the electrical properties are measured. Weight changes from the known initial state indicate the amount of water gained or lost. Using the known CEC, the surface area of the clays and the average thickness of the water can be estimated. Two other methods of adjusting the water saturation in the sample have also been implemented, which are the electroosmosis method and the air-drying method. Under the electroosmosis method, the sample is a long core sample that is impressed with a direct current for a period of time, and after that cut into thin slices. The air-drying method exposes the sample to ambient air under a controlled condition; thus the remaining pore water can be determined. Then, after a period of equilibration, the sample is measured for its electromagnetic properties.

Preservation fluid is also studied thoroughly, as this fluid is very important in preserving the condition of the sample either for short-term or long-term storage. Movement of pore water into or out of the sample is determined by changes in sample weight and changes in electromagnetic properties of the preservation fluid.

This dissertation is a continuation of the author's graduate research that has been previously reported on his Master's report (Adisoemarta, 1995); as such there will be several discussions referring back to that document.

1.2 Report Systematics

This report will be arranged as follows: Chapter I will present the problem statement; Chapter II will give the theoretical background of electromagnetic properties and measurements; some studies that have been done in the past will be presented in Chapter III, followed by the sample preparation techniques in Chapter IV; electromagnetic measurements results are described in Chapter V; the induced DC potential phenomena in Chapter VI; and Chapter VII will present the conclusions.

CHAPTER II

IMPEDANCE IN POROUS MEDIA

2.1 Shale Conductivity Theory

The macroscopic electrical behavior of conducting dielectrics subjected to a harmonic sinusoidal field is described by Maxwell's equations and certain constitutive relationships.

All electromagnetic fields are created from distributions of charges and currents in which the electric field (resulting from the charge distributions), and the current densities (from the current distributions) are related through the complex transfer functions that result from Maxwell's equations:

$$\nabla \bullet E + \partial B / \partial t = 0 \tag{2.1}$$

$$\nabla \bullet H - \partial D / \partial t - J = 0 \tag{2.2}$$

and with the conservation of charge defined as:

$$\nabla \bullet J - \partial q / \partial t = 0 \tag{2.3}$$

are the five components of the electromagnetic field, where:

E = electric field intensity (volt/meter)

B = magnetic flux density (webers/meter^2)

H = magnetic field intensity (ampere-turn/meter)

D = electric displacement (coulomb/meter^2)

J = electric current density (ampere/meter^2)

q = charge density (coulomb/meter^3).

For the case of homogeneous, isotropic, and a non-zero electrical conductivity medium, the electric field becomes

$$\nabla \bullet E = 0 \ . \tag{2.4}$$

For the case of materials that exhibit electromagnetically linear behavior, the following relationships are valid:

$$D = \varepsilon E \tag{2.5}$$

$$J = \sigma E \tag{2.6}$$

$$B = \mu H \tag{2.7}$$

where

ε = dielectric permittivity (farad/m)

σ = electric conductivity (mho/m or siemens/m)

μ = magnetic permeability (henry/m).

The equation for total current density, J_T , is the result of solving equations (2.2), (2.5), and (2,6):

$$J_T = \nabla \bullet H = \sigma E + \varepsilon dE/dt \tag{2.8}$$

where σE is the conduction current component (in phase with applied voltage), and $\varepsilon dE/dt$ is the displacement current component (the out of phase response).

For the time-harmonic case, in which temporal behavior, E_T , described by

$$E_T = E_o e^{-j\omega t} \tag{2.9}$$

where

j $= (-1)^{1/2}$

ω = frequency (radians / sec),

the total current density J_T in a medium becomes the following:

$$J_T = (\sigma^* - j\omega\varepsilon^*) E_T \tag{2.10}$$

where σ^* and ε^* are, in general, complex scalars dependent upon frequency (Fuller and Ward, 1970).

By substituting these complex scalars, with their respective real (shown with a single prime, ') and imaginary (shown with a double prime, ") components,

$$\sigma^* = \sigma' - j\sigma'' \tag{2.11}$$

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \tag{2.12}$$

equation (2.10) can be rewritten as the following:

$$J_T = (\sigma_{eff} - j\omega\varepsilon_{eff}) E_T \tag{2.13}$$

where $\sigma_{eff} = \sigma' + \omega\varepsilon''$ and $\varepsilon_{eff} = \varepsilon' - \sigma''/\omega$ are real functions of frequency that constitute the experimentally measured rock parameters (Fuller and Ward, 1970).

In the simplest form, equation (2.13) becomes the familiar Ohm's law that relates electric current to the voltage across the medium and the conductance of the medium itself. Ohm's law is as follows:

$$I = GV \tag{2.14}$$

where

I = electric current (amperes)

G = electric conductance (mho or siemens)

V = electric potential (volt).

2.2 Conductivity and Susceptivity

The output from the measurement equipments are not directly comparable to each other, and they have to be converted to conductivity and susceptivity before they can be compared to each other. For the impedance analyzer, the outputs are resistance and

reactance. The conversions to resistivity, reactivity, conductivity and susceptivity are calculated using the equations below:

$$r = \frac{R\pi d^2}{t} \tag{2.15}$$

$$x = \frac{X\pi d^2}{t} \tag{2.16}$$

$$g = \frac{r}{r^2 + x^2} \tag{2.17}$$

$$b = \frac{-x}{r^2 + x^2} \tag{2.18}$$

where

R = resistance (ohm)

X = reactance (ohm)

r = resistivity (ohmmeter)

x = reactivity (ohmmeter)

t = sample thickness (meter)

d = electrode diameter (meter)

g = conductivity(Siemens/meter)

b = susceptivity (Siemens/meter).

For the network analyzer, the outputs are in real and imaginary (in-phase and out-of-phase) permittivity, and the conversions to conductivity and susceptivity are as follows:

$$g = \omega\varepsilon_0\varepsilon'' = \sigma_{eff} \tag{2.19}$$

$$b = \omega\varepsilon_0\varepsilon' = \omega\varepsilon_{eff} \tag{2.20}$$

where

g = conductivity (Siemens/meter)

b = susceptivity (Siemens/meter)

ε' = relative permittivity, real part (dimensionless)

ε'' = relative permittivity, imaginary part (dimensionless)

$\varepsilon_0 \cong 8.854 \times 10^{-12}$ (Farads/meter).

2.3 Dissipation Factor

A dielectric parameter that will be used in this research is the dissipation factor. The dissipation factor is defined as the ratio of in-phase to quadrature current components:

$$D = \frac{\varepsilon''}{\varepsilon'} \quad . \tag{2.21}$$

2.4 Dimensionless Properties

Two dimensionless properties that will be used in this report are the dimensionless forms of effective conductivity and effective permittivity.

The dimensionless effective conductivity is

$$\sigma_{eff_D} = \frac{\sigma_{eff}}{\omega \varepsilon_0} \quad . \tag{2.22}$$

The dimensionless form of effective permittivity is

$$\varepsilon_{eff_D} = \frac{\varepsilon_{eff}}{\varepsilon_0} \quad . \tag{2.23}$$

2.5 Electromagnetic Measurement Techniques

There are several methods in the frequency-domain for measuring electromagnetic properties of materials, and the most popular methods are described herein.

2.5.1 Parallel-Plate

The material under test is formed as a thin flat sheet and sandwiched between two electrodes, thus making a capacitor, as shown in Figure 2.1. This method is very dependable and very easy to implement.

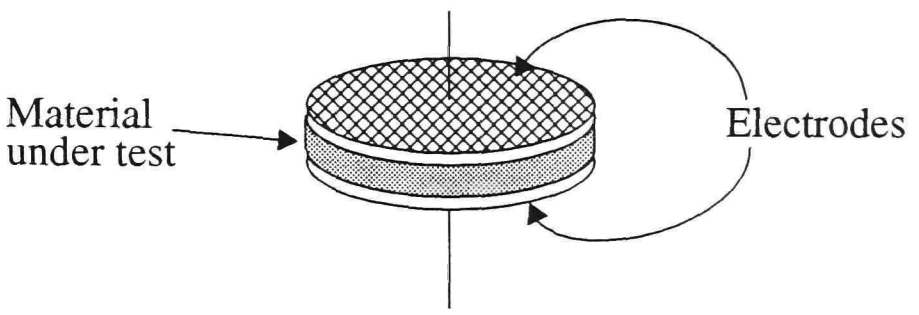
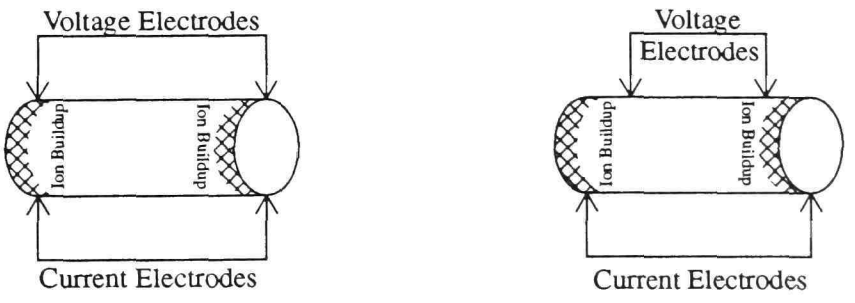


Figure 2.1 Parallel - Plate Method

The disadvantages of this method are a frequency limit of around 15 MHz; "fringe effect" or the stray current path at the sample edge; necessity for a smooth, flat with parallel faces sample; and sample maximum thickness of around 10 mm.

Methods for parallel-plate measurement can be separated into two general categories, which are two-electrode and four-electrode measurements. Figure 2.2 shows these two methods.



Two-Electrode Four-Electrode

Figure 2.2 Two and Four Electrode Setup

The two-electrode measurement is where the set-up is exactly as shown in the Figure 2.1. The sample is placed between two current electrodes, and these electrodes are also the voltage electrode. This method is prone to errors at the lower end of the frequency, less than 10 kHz, due to the contact impedance from the ionic build-up at the sample-electrode interface (Lewis et al., 1986; Garrouch, 1992). The ionic build-up is the zone where the frequency changes are slow enough that ions have sufficient time to "pile up" at the sample-electrode interface. As the frequency increases, the possibility of build-up diminishes, and at sufficiently high frequency, the ionic build-up zone vanishes completely. To reduce the effect of ionic build-up, Scott et al. (1967) used a combination of platinized platinum electrodes and blotter pads to increase the surface area at the sample-electrode interface, hence minimizing the ionic build-up.

In a four-electrode set-up, separate voltage electrodes are used at each sample face located away from the current electrodes, outside the ionic build-up zone. As the voltage electrodes have a high impedance, they will draw almost no current, so that essentially no ionic build-up will occur at the voltage electrodes.

2.5.2 Coaxial

The sample is shaped into a core with a hole in the middle and inserted into a short coaxial airline. The center conductor is passed through the hole in the sample, as shown in Figure 2.3. The frequency range of this method is very broad, 100 MHz to 18 GHz.

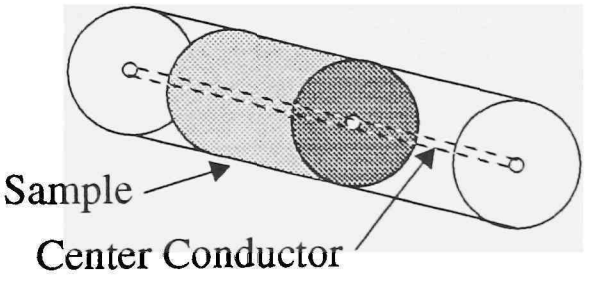


Figure 2.3 Coaxial Method

The disadvantage of this method is that the sample needs to be carefully machined to avoid error due to the presence of an air gap between the sample and the airline wall or the center conductor. Huang and Shen (1983) found that even air gaps of 10^{-3} inches can

introduce an error of up to 60% for the case of highly conductive rock samples. As the conductivity of air is much lower than of the rocks, they found that the air acts as an insulator. To reduce the error, they used a highly conductive saline solution, thus reducing the contrast in conductivity, and making the air gap error negligible. In the case where the sample is a water-bearing formation and can not be disturbed by adding saline solution, a coat of a low melting point alloy can be applied on the sample, as demonstrated by Coutanceau-Monteil (1993).

Another disadvantage of this method is that the sample size has to be small to keep the impedance of the system constant. This constraint in sample dimension might make the sample too small to homogenize the parameter of interest (e.g., dielectric constant. and conductivity). Coutanceau-Monteil (1993) solved this problem by using tapered adapters in which the impedance was kept constant from the analyzer to the coaxial cable to the sample holder and back to the analyzer.

Due to difficulties in machining the sample and the inherent characteristic of shale expanding and shrinking as water content changes, thus causing the dimension to be unable to be constant and maintain its physical fitness inside the airline, the research in this dissertation did not use this method.

2.5.3 Cavity

A microwave cavity is a volume enclosed completely by metallic walls. The sample is placed inside this cavity where microwave energy is trapped and reflected many times through the sample, as shown in Figure 2.4.

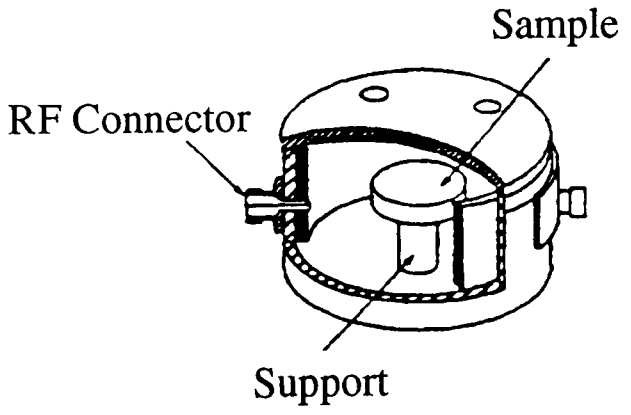


Figure 2.4 Cavity Method (Blackham, 1990)

The change in the electromagnetic response with and without the sample in the cavity is then related to the complex permittivity of the sample-under-test. This method is very sensitive to low-loss dielectrics and requires less sample machining compared to coaxial method. The disadvantage of this method is this method is not broad-band in frequency but single frequency measurement, which is determined by the physical size of the cavity, and is computationally intensive

2.5.4 Open-Ended Probe

The open-ended probe is basically a cut-off coaxial line where the sample touches the face of the probe, as shown in Figure 2.5. The face of the sample must be flat and smooth. The electromagnetic field is reflected off the sample, and the reflection (S_{11}) is related to the complex permittivity of the sample.

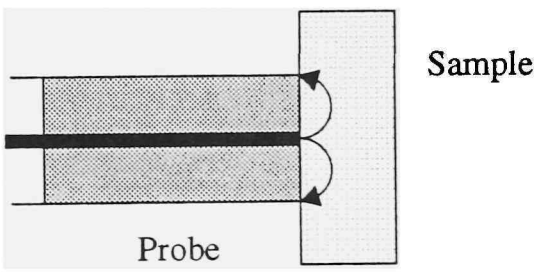


Figure 2.5 Open-Ended Probe

The advantages of this method are that the frequency range is relatively broad (100 MHz up to 2.6 GHz), the probe is very small and portable, the probe can work with both solid and liquid samples, and there is no need to machine the sample for a perfect fit, such as for the coaxial-method. The disadvantage of this method is that because the depth-of-investigation is very small, the reading is mostly affected by a small portion of the sample and is thus very prone to heterogeneity of the sample.

2.6 Methodology Used in This Research

To ensure the quality of measurements, the four-electrode parallel-plate setup is used for the low frequency electromagnetic measurements. Fringe effect is reduced by

using the thinnest sample disks as possible. The Open-Ended probe method is used for the high frequency electromagnetic measurements, as this method is very handy and has fairly broad frequency coverage.

CHAPTER III

CONDUCTIVITY IN POROUS MEDIA

This chapter will cover clay minerals and their double layer properties and will summarize several studies that have been done on the complex dielectric parameters of porous media.

3.1 Clay Minerals

The definition of clay evolve with time, as mention by Guggenheim and Martin (1995), starting from 1546 up to the most recent definition jointly published by the AIPEA (International Association for the Study of Clays) and the CMS (Clay Minerals Society). The most recent definition (Guggenheim and Martin, 1996) is as follows:

> The term 'clay' refers to a naturally occuring material composed primarily of fine-grained minerals, which is generally plastic at appropriate water contents and will harden when dried or fired. Although clay usually contains phyllosilicates, it may contain other materials that impart plasticity and harden when dried or fired. Associated phases in clay may include materials that do not impart plasticity and organic matter. (p. 715)

Clay minerals are only observable under an electron microscope. The individual clay crystals are shaped like plates made of sheets of repeating atomic structure. Fundamentally, the crystal sheets can be seen as only having two types, the tetrahedral or octahedral sheets. Different clay minerals are built from these two structure sheets with various ways of stacking, together with various bonding and different metallic ions in the crystal lattice. Figure 3.1 illustrates the components of a tetrahedral sheet, first consisting of silica tetrahedron units with each unit made of one silicon atom surrounded by four oxygen atom (Figure 3.1.a). These units are joined together to make a hexagonal network (Figure 3.1.b).

The octahedral sheet, as shown in Figure 3.2, is a combination of octahedral units (Figure 3.2.a) that consist of six hydroxyls, surrounding an aluminium, magnesium, or iron atom, joined together to create a sheet (Figure 3.2.b).

In the tetrahedral sheet, Si^{4+} is sometimes partially replaced by trivalent Al^{3+}. In the octahedral sheet, trivalent Al^{3+} can be replaced with divalent Mg^{2+} without completely

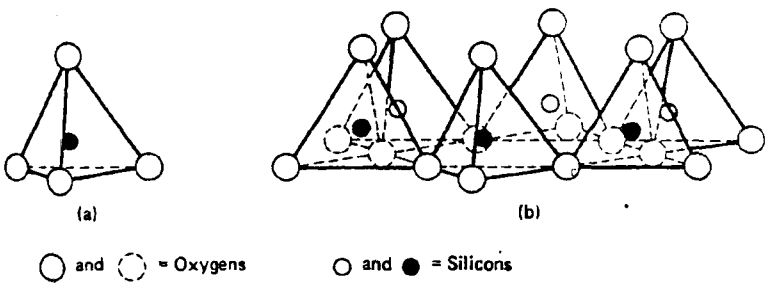


Figure 3.1 Silica Tetrahedron (Eslinger, 1988)

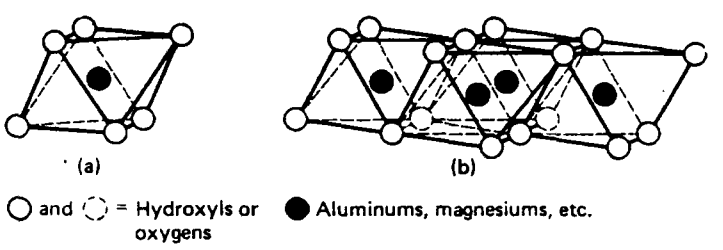


Figure 3.2 Octahedral Sheet (Eslinger, 1988)

filling the vacant octahedral position. Al atoms may also be replaced by Fe, Cr, Zn, Li and other atoms, and the small size of the these atoms permits them to take the place of the small Si and Al atoms. This replacement is often called an *isomorphous substitution* and leads to different clay minerals such as kaolinite (Figure 3.3) and muscovite (Figure 3.4).

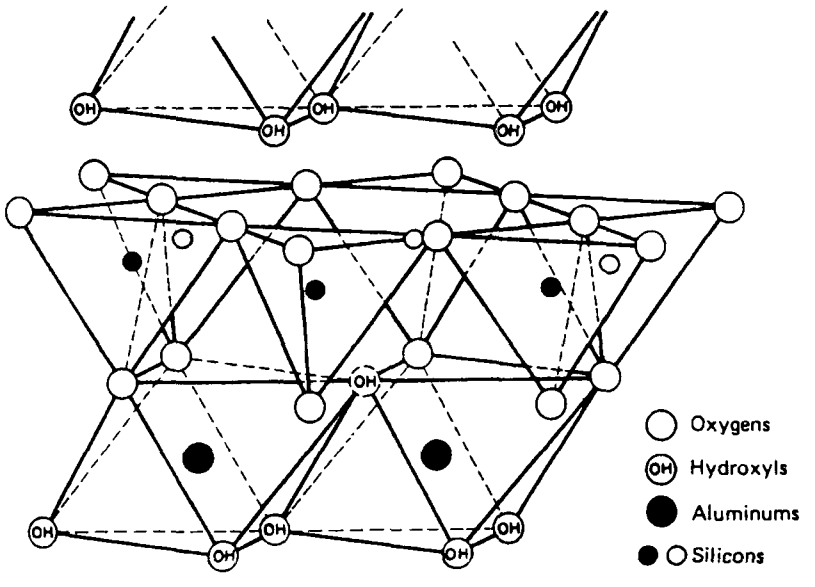
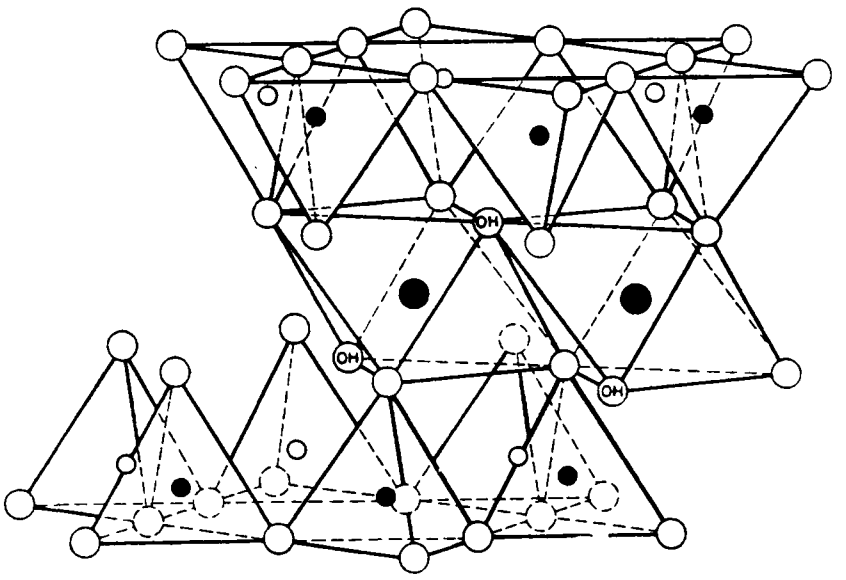


Figure 3.3 Sketch of Kaolinite (Eslinger, 1988)

In many minerals, an atom of lower positive valence replaces one of higher valence, creating a deficit of positive charge and therefore an excess of negative charge. This excess of negative charge is compensated by the adsorption on the layer surfaces of cations, which are too large to be accommodated in the interior of the lattice. In the presence of water, the compensating cations on the layer surfaces may be easily exchanged by other cations when available in solution; they are called exchangeable cations. Analytical methods can determine the amount of these cations. This amount, expressed in milliequivalents per 100 grams of dry clay, is called the *cation exchange capacity* (CEC).



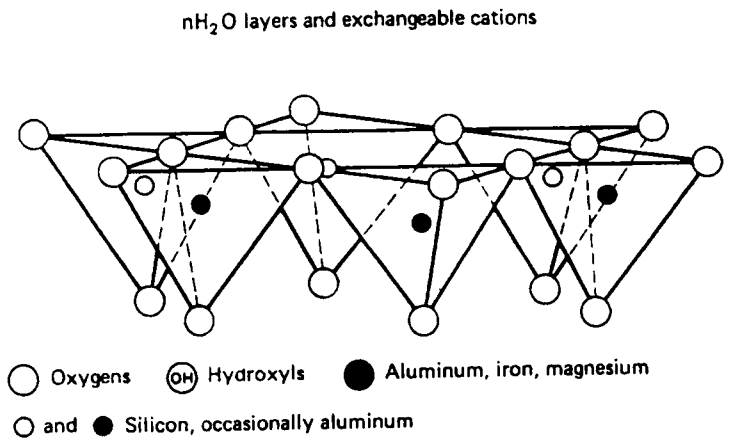


Figure 3.4 Sketch of Muscovite (Eslinger, 1988)

Figures 3.5 and 3.6 show a method to make the sheet in the clay minerals easier to visualize, by using "schematic representation" of the tetrahedral or octahedral sheets. Figure 3.6 also shows arrows that point to the inter-layer gap on montmorillonite where water and exchangeable ions can enter and separate the layers that are held together by weak

bonding (van der Waal's bonding) between the tops of the silica sheets, and the net negative charge deficiency in the octahedral sheet.

The inter-layer, also called intra-crystalline, swelling that occurs after montmorillonite clays are contacted with water or water vapor, will generate more or less stable configuration of the hydrated clay, corresponding to the presence of one to four monomolecular layers of water between the unit layers.

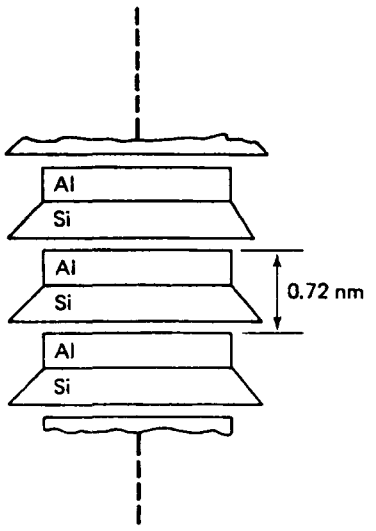


Figure 3.5 Schematic Diagram of the Structure of Kaolinite (Holtz and Kovacs, 1981)

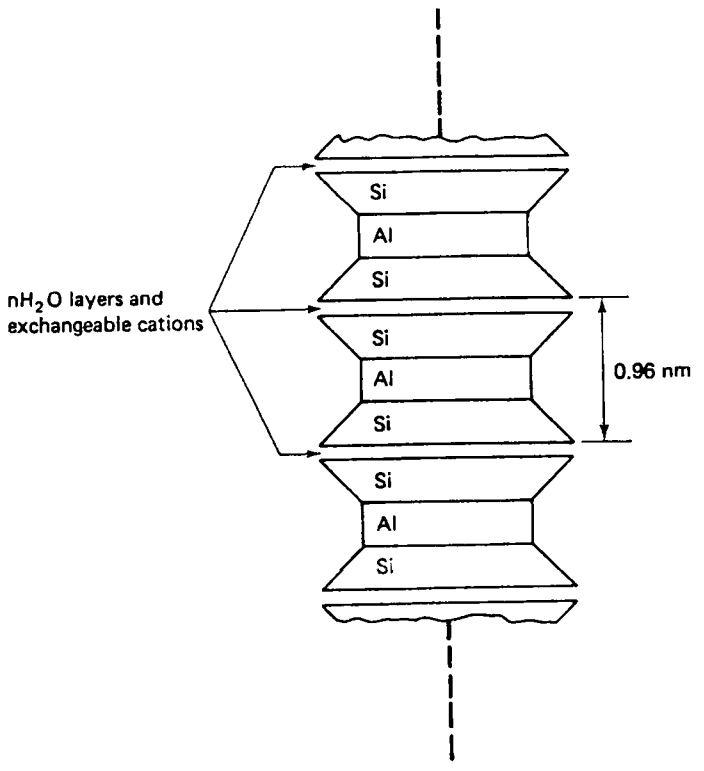


Figure 3.6 Schematic Diagram of the Structure of Montmorillonite (Holtz and Kovacs, 1981)

3.2 Electric Double Layer

The preceding section shows that, as a result of isomorphous substitutions by elements of lower valence, the clay lattice carries a net negative charge. The net negative lattice charge is compensated by cations that are located on the unit-layer surface. The cations diffuse in the presence of water, as their concentration will be smaller in the bulk solution. But, due to the charged lattice, these cations will also be attracted electrostatically, and the result of these opposing trends is the creation of a distribution of compensating cations in a diffuse electrical double layer on the exterior layer surfaces of a clay particle. Olphen (1963) mentioned that this distribution of charge is analogous to that in the earth's atmosphere where the gas molecules are both attracted to the earth by gravitation and diffusion to the outer space. There are two models that are commonly used to explain the double layer, the Gouy-Chapman Model and Stern Model.

3.2.1 The Gouy-Chapman Model

An electric double layer consists of a surface charge and a compensating counter-ion charge that creates a "cloud" of ions with a diminishing concentration away from the charged surface (Figure 3.7). This model assumes that the ions in the fluid are point charges, the fluid is a continuous medium, and only the dielectric constant properties of the fluid affects the double layer. From the electrostatic and diffusion (Poisson-Boltzmann) theory, the exact distribution of positive and negative ions can be determined as a function of distance from the surface. The net charge concentration distribution, ρ , for any position from a positively charged surface can be derived as a function of the potential Ψ:

$$\rho = ze\,(n_+ + n_-) = -2n_o ze \sinh\frac{ze\Psi}{kT} \tag{3.24}$$

where

n_o = ion concentrations in the bulk electrolyte

n_+ = ion concentrations of the positive ions

n_- = ion concentrations of the negative ions

T = temperature

k = Boltzman constant

z = ion valence

e = electron charge.

The potential, Ψ, away from the surface can be solved by utilizing the Poisson equation, and ends up as the Poisson-Boltzmann equation:

$$\nabla^2\Psi = \frac{8\pi n_o ze}{D}\sinh\frac{ze\Psi}{kT} \tag{3.25}$$

with D as the dielectric constant of the medium. This net charge in the diffuse layer should be equal to the charge on the surface to satisfy the electroneutrality:

$$\sigma = -\int ze\,(n_+ - n_-)\,dx \tag{3.26}$$

where surface charge density on the surface is denoted as σ.

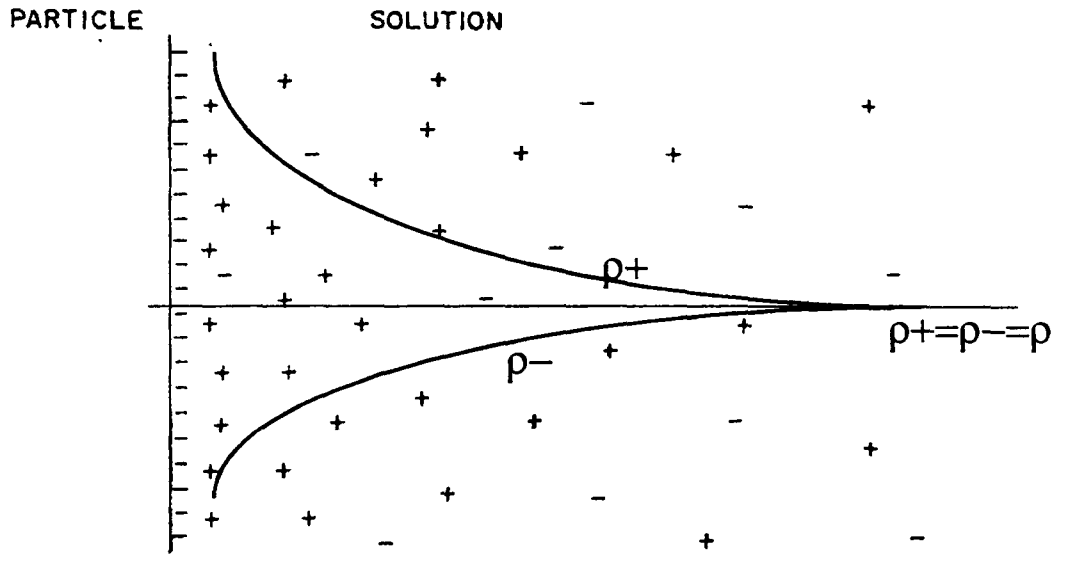


Figure 3.7 Diffuse Electric Double-layer According to Guoy-Chapman (Olphen, 1963) Overlaid With Potential Distribution ρ

The Gouy-Chapman model of the electric double layer contains some unrealistic elements, such as ions treated as point charges and neglect of the finite dimensions of the ions. Also, the specific interactions between the surface, counter-ions and medium are ignored. These assumptions are tolerable in dilute solutions where the diffuse layer is wide, but in concentrated electrolytes, this model fails.

3.2.2 Stern Model

This model considers that the distance of closest approach of a counter-ion to the charged surface is limited by the size of these ions. Figure 3.8 shows that the counter-ion charge is separated from the surface charge by a layer of thickness δ in which there is no charge. This setup basically creates an electric condenser of molecular size, formed by the surface charge and the charge in the place of the centers of the closest counter-ions. In this condenser, also called the "Stern layer," the electric potential drops linearly with distance from a value Φ_0 at the surface to the Stern potential, Φ_δ. The remaining part is distributed as in a diffuse Gouy-Chapman atmosphere.

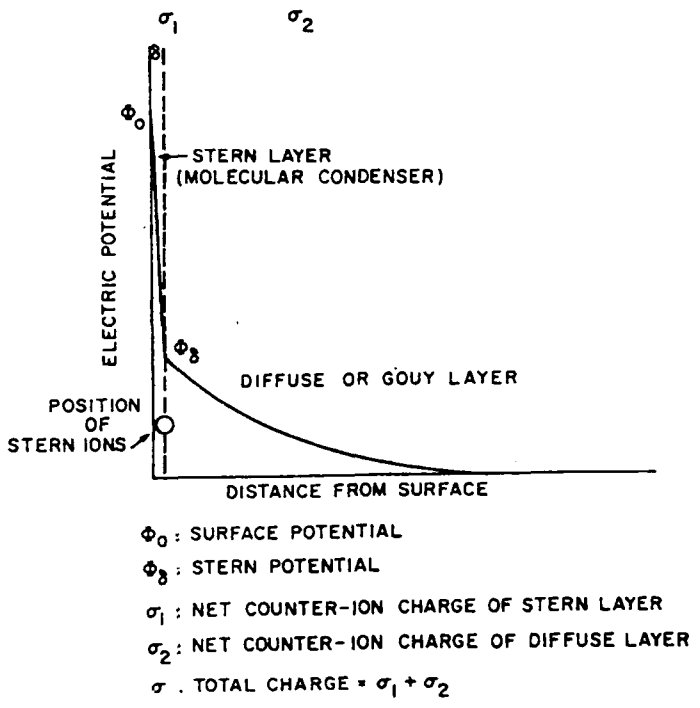


Figure 3.8 Potential Distribution of Stern's Electric Double Layer (Olphen, 1963)

The total counter-ion charge in this model is split between the charge inside the condenser (σ_1) and the charge in the diffuse atmosphere (σ_2); the sum is equal to the surface charge (σ).

3.3 Dielectric Models of Clayey Media

The most widely used formula, and also the simplest to describe the electrical conductivity on porous rock, is Archie's law, defined in conductivity form as

$$\sigma_o = \sigma_w \, a \, \phi^m \tag{3.27}$$

where

σ_o = electrical conductivity of fully fluid saturated rock

σ_w = electrical conductivity of saturating fluid

ϕ = pore volume fraction

a = empirical parameter

m = empirical parameter (cementation factor)

and formation factor, F, is defined as the ratio of σ_w / σ_r.

For the case of a partially water saturated condition, Equation (3.4) becomes

$$\sigma_t = \left[\frac{S_w^n}{F} \right] \sigma_w \tag{3.28}$$

where

σ_t = electrical conductivity of partially saturated rock

S_w = fractional water saturation

n = saturation exponent.

Archie's model assumes that electrical conduction through the saturating fluids in the pores is the dominant factor, and surface conduction along pore walls is negligible. This model would fail in porous media that has even a small amount of clay in the pores, as surface conduction due to cation exchange would be a significant factor. However, the magnitude of the surface conductance effect is also a function of salinity of the pore water and the CEC of the clay minerals. Several models that have been proposed to modify Archie's model to include the clay effect will be discussed herein.

3.3.1 Waxman-Smit (1968)

The modification of Archie's model with the extra surface conduction and cation exchange capacity in shale and clay-bearing sands results in the following equation:

$$\sigma_o = (\sigma_w + BQ_v)\, a\, \phi^m \tag{3.29}$$

or

$$\sigma_o = [1/F]\, (\sigma_w + BQ_v) \tag{3.30}$$

where

B = equivalent conductance of counter-ions associated with clay in pore water, determined empirically as

$B = 4.6\ (1 - 0.6\ e^{-0.077\sigma w})$

Q_v = cation exchange capacity per unit pore volume.

For a partial water saturated pore condition, Equation 3.6 becomes

$$\sigma_t = (\sigma_w S_w^{\ n} + BQ_v S_w^{\ p})\ a\ \sigma^m \tag{3.31}$$

where

p = clay content as a fraction of the bulk volume.

3.3.2 Dual-Water (Clavier et al., 1977)

This model enhances the Waxman-Smit model by assigning a specific "volume" to the clay contributed conductivity in addition to the clay-free water conductivity. Hence this model is called the "Dual-Water" (DW) model, as there are two water types that are being predicted by the model, both for its conductivity and its volume fraction.

The first water is the *clay water*, which surrounds the clay particles. Its conductivity, σ_{cw}, comes from the clay counterions. The volume fraction, V_{cw}, is directly proportional to the counterion concentration, Q_v

$$V_{cw} = \nu_Q\ Q_v\ \phi_t \tag{3.32}$$

where

ν_Q = the amount of clay water associated with 1 unit (meq) of clay counterions

ϕ_t = total porosity.

The other water is the *far water*, the water that is farther away from the clay. This water has conductivity, σ_w, and ionic concentration that corresponds to the salinity of bulk--formation water. The volume fraction of free water, V_{fw}, is the remainder of the total water content subtracted by the clay water

$$V_{fw} = V_w - V_{cw} = (S_{wT} - \nu_Q Q_v)\,\phi_t\,. \tag{3.33}$$

The equivalent fluid conductivity of the formation is the combination of these two fluids using the volumetric weighted averaging method:

$$\sigma_{we} = \{\,(S_{wT} - \nu_Q Q_v)\,\sigma_w + \nu_Q Q_v \sigma_{cw}\,\} / S_{wT}. \tag{3.34}$$

The partially saturated conductivity will be as follows:

$$\sigma_t = \frac{S_{wT}^n}{F}\left[\sigma_w + \frac{\nu_Q Q_v}{S}(\sigma_{cw} - \sigma_w)\right]. \tag{3.35}$$

3.3.3 Lima and Sharma (1992)

This model assumes that clays are charged particles surrounded by a counterion double layer in which the polarization occurs. This model has two sub-models with differing assumption on the polarization of the double layer. The first one is the S-model where a Stern layer is included, but radial fluxes are assumed to be small. The second model is the D-model, which assumes that only the diffuse layer polarizes. Comparison with experimental data showed that the S-model is suitable for cases in which most of the counterions are tightly bound to the solid particles, but any ionic diffusion will make the prediction of conductivity and permittivity higher than the actual observed values. The D-model is more appropriate for representing the dielectric behavior of clay bearing rocks in the range from 1 to 10^7 Hz.

3.3.4 Knight and Nur (1984)

This study used a variety of sandstones representing a range in porosity from 6% to 28%, in permeability from microdarcies to millidarcies, and in clay content from 0% to 18%. The dielectric constants of these sandstones were measured across the frequency range of 5 Hz to 13 MHz as a function of water saturation and pore fluid salinity.

The measurement electrodes consisted of a 1000Å thick platinum layer sputtered onto the two flat faces of each disc-shaped sample. This technique makes a reversible

electrode in which an electrochemical reaction will occur such that there is an exchange of charge carriers across the interface, preventing a build-up of ions and/or electrons.

This study found that a Debye circuit provides a good equivalent circuit with which to approximately model the response of the samples. The Debye circuit contains two capacitors – one in series and one in parallel with the d.c. resistance of the sample.

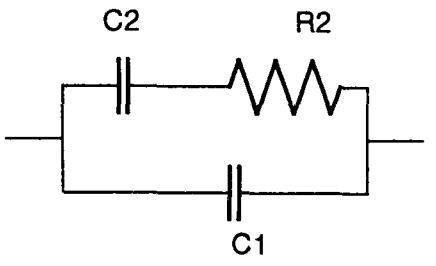


Figure 3.9 Debye Circuit

The impedance due to a capacitor, which is reactance (χ_s), is represented by the following:

$$\chi_s = \frac{1}{\omega C} \tag{3.36}$$

which means that the impedance of the two capacitors, C1 and C2 varies with frequency. At low frequency, the impedance of C1 will be high so that no current will flow through that portion of the circuit; thus the circuit is effectively a series RC circuit (R2 in series with C2) at low frequencies. At high frequency, the impedances of both C1 and C2 decrease. The impedance of C2 decreases to the point where current will flow through that part of the circuit; the impedance of C2 decreases to essentially zero, leaving a parallel RC circuit (R2 in parallel with C1). The study found that the values of the two capacitors are approximately 10^{-3} and 10^{-11} Farads, with the former, C1, dominating the low frequency and the latter, C2, the high frequency response.

The observed change of the dielectric constant with water saturation is interpreted as reflecting the presence of bound and free water in the pore space of a rock sample. The result is a rapid increase with saturation in the dielectric constant at low saturation up to some critical saturation above which the dielectric constant increases linearly and more

gradually with saturation. The critical saturation is interpreted as reflecting the percentage of bound water in the rock and is thus proportional to the surface-to-volume ratio of the pore space.

3.3.5 Garrouch (1992)

This dissertation studies the effects of wettability, clay content, water saturation and salinity on the electrical properties of hydrocarbon-bearing rocks. The frequency range of interest is 10 Hz to 10 MHz. Measurements were made for the impedance of both fully and partially saturated rocks using the four-electrode method for the latter, and the two-electrode method for the former. These measurements include both clean and shaly sand samples.

For fully saturated rocks, this study found that the dielectric constant increases with the clay volume fraction, the cation exchange capacity, and the electrochemical potential of the fluid saturating the rock samples. It is found to decrease with increasing salinity, frequency, permeability, and porosity. Neither stress nor wettability appear to significantly influence the dielectric constant of fully brine-saturated Berea cores.

The study has also inverted the Lima-Sharma theory for modelling the complex impedance of partially saturated shaly sands. This inversion allows a log analyst to use low frequency (less than 1 KHz) and high frequency (higher than 1 MHz) complex impedance data from well logs to calculate in-situ reservoir petrophysical parameters such as water saturations in the virgin formation and in the flushed zone, porosity, clay volume fraction, clay surface charge density, and grain size. The result of the inversion method was implemented using real well log input, resulting in a reasonably good output of reconstructed log. The slight discrepancy between the actual values and the output model values are possibly due to the finite difference method solution.

CHAPTER IV

SAMPLE PREPARATION AND PRESERVATION

This chapter will describe the sample preparation including sample dimension requirements, cutting procedures, preconditioning, and preservation stages.

4.1 Sample Dimension Requirements

The main requirement for the sample dimension is to be able to use the same shale sample on both parallel-plate and open-ended coaxial probe setups.

Diameter. The sample diameter has to be around the 2 inch (5.08 cm.) diameter of the parallel-plate electrodes. This sample diameter also fits the requirement for the open-ended coaxial probe, as it requires a sample diameter greater than 2 cm. (HP, 1993).

Thickness. The maximum sample thickness is determined by the parallel-plate set-up, which is around 10 mm, and the minimum thickness is determined by the open-ended probe specification. The depth of investigation of the open-ended coaxial probe is a function of the sample's relative permittivity and defined as the following equation (HP, 1993):

$$d\,(mm) = \left(\frac{20}{\sqrt{\varepsilon_r}}\right) \tag{4.1}$$

where

d = minimum thickness (mm)
ε_r = dielectric constant.

A low dielectric constant sample will be the worst case scenario for the open-ended probe as the depth of investigation will be the deepest. Assuming that the lowest dielectric constant of the sample is 6, for a typical dry sandstone sample, then the depth of investigation is around 8.2 mm. Hence the sample thickness has to be between 8.2 and 10 mm. For the case of 10 mm sample thickness, Equation 4.1 indicates that the lower bound dielectric constant that can be measured is 4.

Parallel sample faces are very important for the parallel plate setup, as the sample is the capacitive medium between the electrodes, and any deviation from a perfect parallel sample makes the result questionable.

Sample flatness is another parameter that has to be defined carefully, as it determines the contact condition for both the parallel-plate setup and the open-ended coaxial probe to the sample. A bad sample-electrode contact will put an air gap in between the sample surface and the electrode, and create an "air-gap error." The severity of such error has been discussed in the past (Rau, 1980; Huang and Shen, 1983; Knight, 1984). The open-ended coaxial probe requires samples to have flatness of less than 25 μm.

After combining the above requirements, the sample specification is as follows: sample surface flatness within 0.001 in (25 μm), parallel sample surfaces within 0.005 in, and a sample thickness between 8 - 10 mm. The sample diameter is 2 in (5.08 cm).

4.2 Sample Preparation

The typical sample cutting method, using a clamp on a bench top saw, rarely gives a good sample cut as the corner of the cut usually nicks when the unclamped part falls off from the main body near the end of the slicing process. This method is also prone to bad parallelness as the manual handling of the core can not maintain the same orientation with respect to the saw blade. Typically it takes a couple of days of manual sample sanding and face lapping to bring those kind of samples to the required specification; thus the typical sample cutting method is very time consuming and labor intensive. To avoid that kind of problem and to ensure a good sample surface after each cutting, a technique of casting the sample in an acrylic tube has been used. Figure 4.1 shows that the sample is held tightly inside the clear acrylic tube by three (3) plastic rods that act as spacers, and the gap is then filled with epoxy. This method will guarantee a smooth and parallel sample surface, as the sample will not wobble and/or rotate while being cut, and also will not break unevenly at the edge when the small piece of the sample breaks off. Even with this technique, a small amount of time for sample face lapping is still needed to meet the required specifications. This sample casting method cuts the sample preparation time from several days to about one hour.

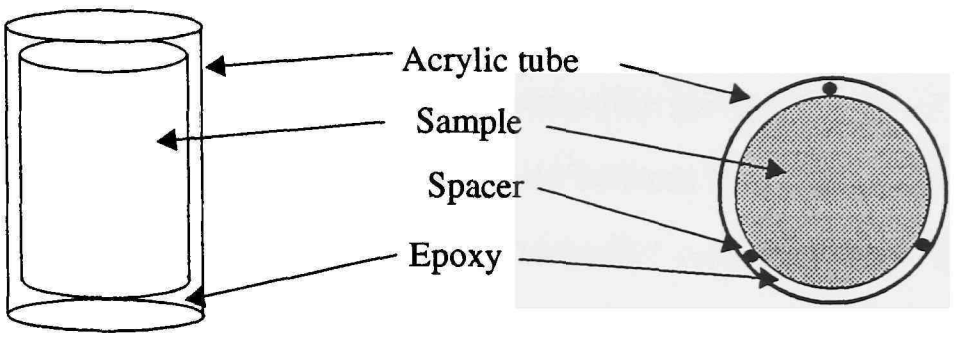


Figure 4.1 Sample Casting

One disadvantage of this method is the core sample can not be cut right away after casting but needs at least 14 hours for the epoxy to harden. Another method was devised for the case of urgent sample slicing in which the core is held inside a two-piece plexyglass sample holder as shown in Figure 4.2. This sample holder holds the sample tightly so the sample will not rotate and has 6 slots for the cutting blade to go throrough. This sample holder allows 5 slices in one cutting session with the certainty that the sample never rotate and that no nicks occur as all the cut slices are held inside the holder. Hence, no slice will fall down to the cutting tray or oil pan until the operator opens the sample holder.

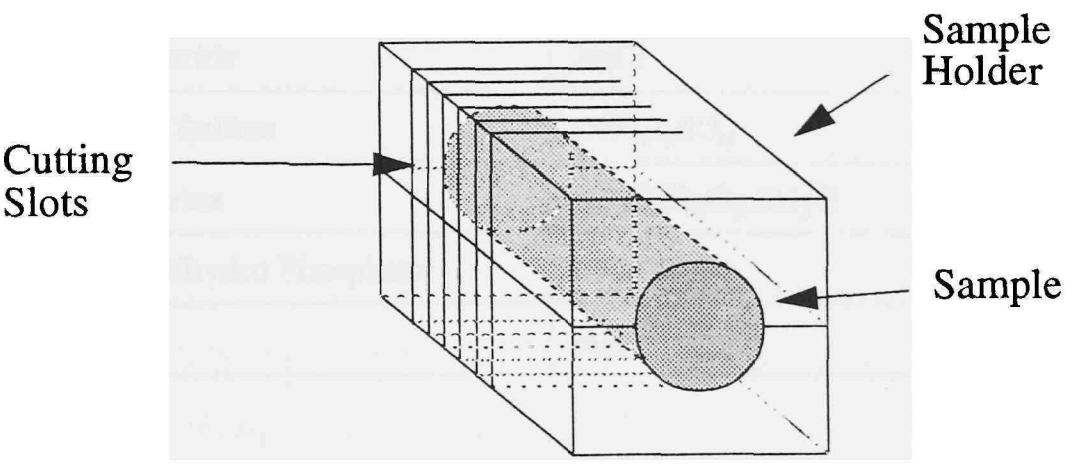


Figure 4.2 Quick Cut Sample Holder

4.3 Sample Conditioning

Each individual shale sample for this research was preconditioned to ensure that no air was entrapped in the shale pore space. This preconditioning was taken to avoid any measurement artifacts due to entrapped air (Forsans and Schmidt, 1994). First, the

moveable water was removed from the sample by oven drying at 99° C for several days until the sample weight remained constant. Next, the sample is resaturated in a controlled way by increasing, in steps, the level humidity environment inside a desiccator. The desiccator had a saturated salt solution on the bottom that released or absorbed water vapor inside the desiccator to make the water humidity equal to the salt solution's water activity. This procedure typically takes a couple of weeks to finish and ensures that no air is entrapped inside the sample pores. Table 4.1 shows the water activity for several salt solutions (Winston, 1960) that were used in this research. By definition

$$\text{Water activity (fraction)} = \text{Relative Humidity (\%)} / 100. \tag{4.2}$$

The terms "relative humidity" and "water activity" are used interchangeably throughout this report.

Table 4.1. Salt Water Activity

No	Salt	Composition	Water Activity
1	Calcium Chloride	$CaCl_2$	0.295
2	Calcium Nitrate	$Ca(NO_3)_2$	0.505
3	Sodium Chloride	NaCl	0.755
4	Ammonium Sulfate	$(NH_4)_2SO_4$	0.800
5	Sodium Tartrate	$Na_2C_4H_4O_6.2H_2O$	0.920
6	Potassium Dihydro Phosphate	KH_2PO_4	0.960
7	Water	H_2O	1.000

Another procedure that was tried for the drying stage was exposing the sample to ambient air (as the ambient air in the lab is relatively dry), for a couple of days until the sample weight stopped changing. Then the sample was brought back up to its original sample weight like the oven dried one. Figure 4.3 shows a typical sample relative weight (the ratio of current sample weight to its original weight) changes as a function of water activity for the two cases of drying. Both methods brought the sample back to its original weight at the sample's native water content.

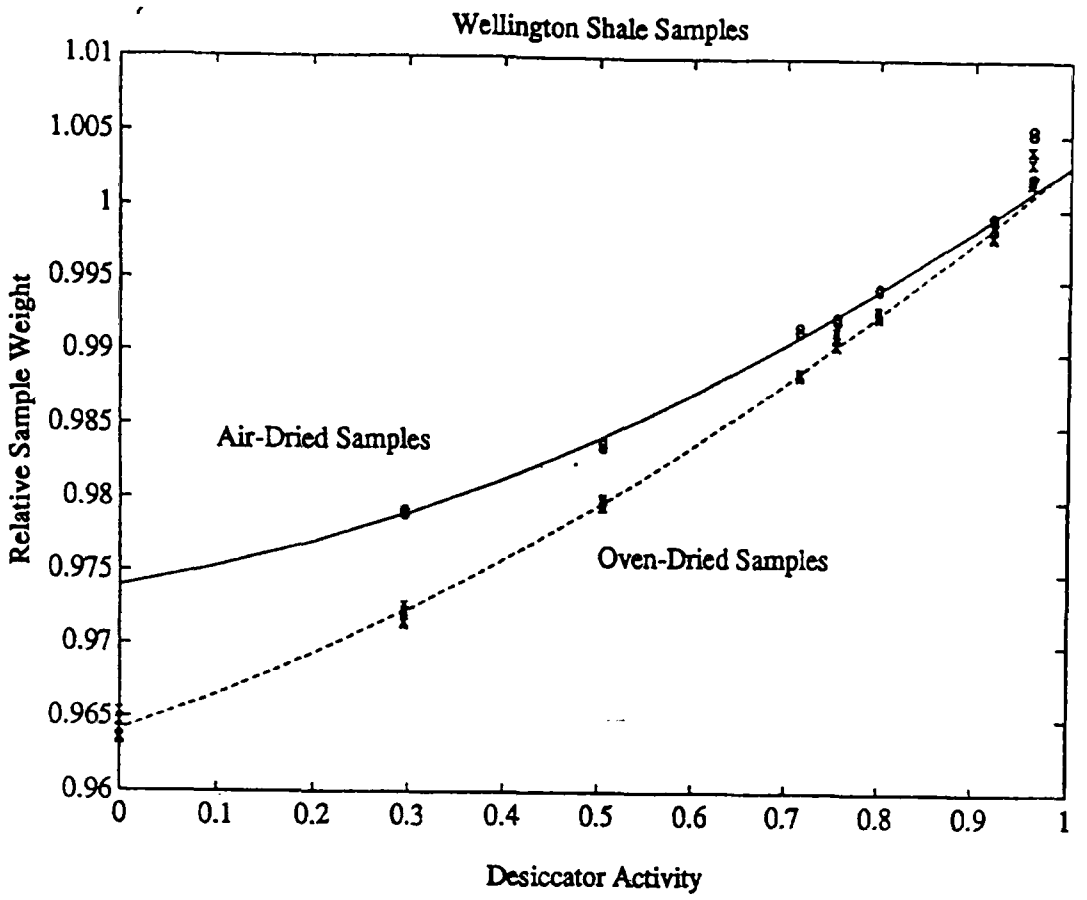


Figure 4.3 Weight Change as a Function of Water Activity (Adisoemarta et al., 1995)

4.4 Shale Properties

The two shales used in this research were Pierre and Wellington. The Pierre Shale, dark grey in color, is from the Upper Cretaceous age and was cored in eastern Colorado. The Wellington Shale is dark grey in color and from the Cretaceous age, but with a lower clay content than the Pierre. This shale was cored in central Utah. Table 4.2 shows the results of the X-ray diffraction tests for weight % of both samples.

Using nominal values of density for each component, the grain density of Pierre is 2.73 g/cc and for Wellington is 2.71 g/cc. Water content of the shale samples were determined from their native and dried weight, and were found as 6.4% and 2.78% by weight for Pierre and Wellington, respectively. Total porosity of Pierre at its native state, defined here

in terms of the moveable water by the drying process, is 14.9%, and for Wellington is 7.0%. The CEC of the Pierre shale is 19.8 meq/100g, and for Wellington is 9.4 meq/100g.

Table 4.2. X-Ray Diffraction Bulk Analysis Results
(Javalagi, 1990)

Crystalline Components	Weight % in Crystalline Portion	
	Pierre	Wellington
Smectite	9	0
Illite	20	12
Kaolinite	2	2
Chlorite - Fe	2	1
Calcite	1	14
Dolomite	1	5
Pyrite	4	4
Feldspar - Na	9	5
Feldspar - K	9	2
Quartz	43	56

4.5 Preservation Fluid

One question that came up during the research is "what fluid should we use to preserve the shale sample that will retain the shales' original physical/electrical properties?" The customary preservation fluid in the petroleum industry is kerosene, but there was no known investigation on the effectiveness of preserving shale samples other than kerosene is readily available and inexpensive (Hale, 1992). A good preservation fluid is needed for this research for both long and short term storage. The long term storage requirement is to ensure that the sample properties will not change with time, and the short term requirement is for the confinement fluid during each of the electromagnetic measurements on the sample so that the sample will not be in contact with air to avoid drying the sample.

To answer the above question, four different fluid samples and two test methods were used. The fluids tested were generic kerosene, Isopar M^{TM} (a mineral oil), Silicon Oil (a synthetic oil), and saturated Isopar M. The saturated Isopar M fluid is the regular

Isopar M oil that has been saturated with water by mixing the fluid with deionized water in a glass jar, agitating vigorously and leaving it to settle for one week. The saturated oil is then siphoned off the top portion of the jar at the moment the fluid is tested. The oil is saturated to reduce the tendency of pore fluid to move out into the confining fluid because water solubility of Isopar M, even though very small, is already fulfilled by the saturating deionized water. Silicon Oil as a preservation fluid was suggested by Olhoeft (1994). Because this fluid is very viscous, it will not enter the sample and also has a very low water solubility; hence, there is no movement of pore water from the sample to the confinement fluid.

The two test methods are: (1) measuring the changes in sample buoyancy and relating those changes to the amount of the pore fluid that leaves the sample, and (2) measuring the changes in the electromagnetic properties of the confinement fluids before and after sample immersion.

4.5.1 Buoyancy Method

For the buoyancy method, a simple sample holder that was fabricated suspended the shale sample directly underneath the analytical balance's main axis and at the same time unloaded the balance's measurement pan. This sample holder also retains any debris that falls off of the sample. Figure 4.4 shows the measurement setup.

For the buoyancy method test, each fluid tested used a preconditioned Pierre shale sample of around 64 gr. of weight, and the changes in buoyancy were recorded at a predetermined time with a personal computer.

Figure 4.5 shows the comparison of the tested fluids. As can be seen, in the first 4 minutes, all tested fluid showed an increase in weight of the shale sample. This increase of weight is due to the loss of buoyancy as the shale was shrinking slightly due to water in the pores that was in contact with the confining fluid that left the pore space into the fluid. The Silicon oil was the worst performer as the rate of loss was the highest. Kerosene, the de-facto preservation fluid in the industry, was not much better as the fluid continuously shrank the sample by taking the pore fluid out. The next fluid, Isopar M, showed an interesting trend. The first 4 minutes, it made the sample shrink, but then the sample slightly swelled

due to a counter flow of oil into the sample. After 15 minutes the rate of water loss overcame the incoming rate and made the sample shrink again. By saturating the oil, this behavior can be slowed down and takes 3 times longer to occur

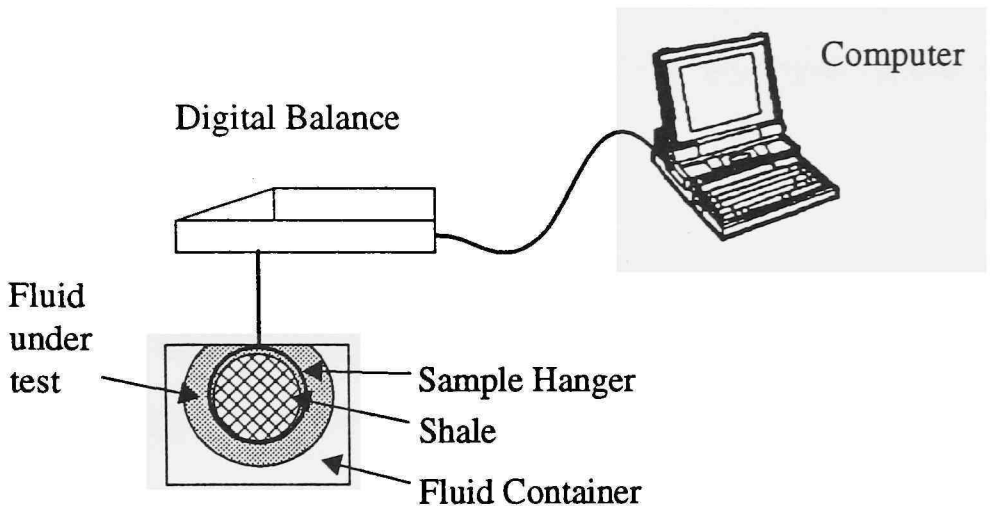


Figure 4.4 Buoyancy Measurement Setup (Adisoemarta et al., 1995)

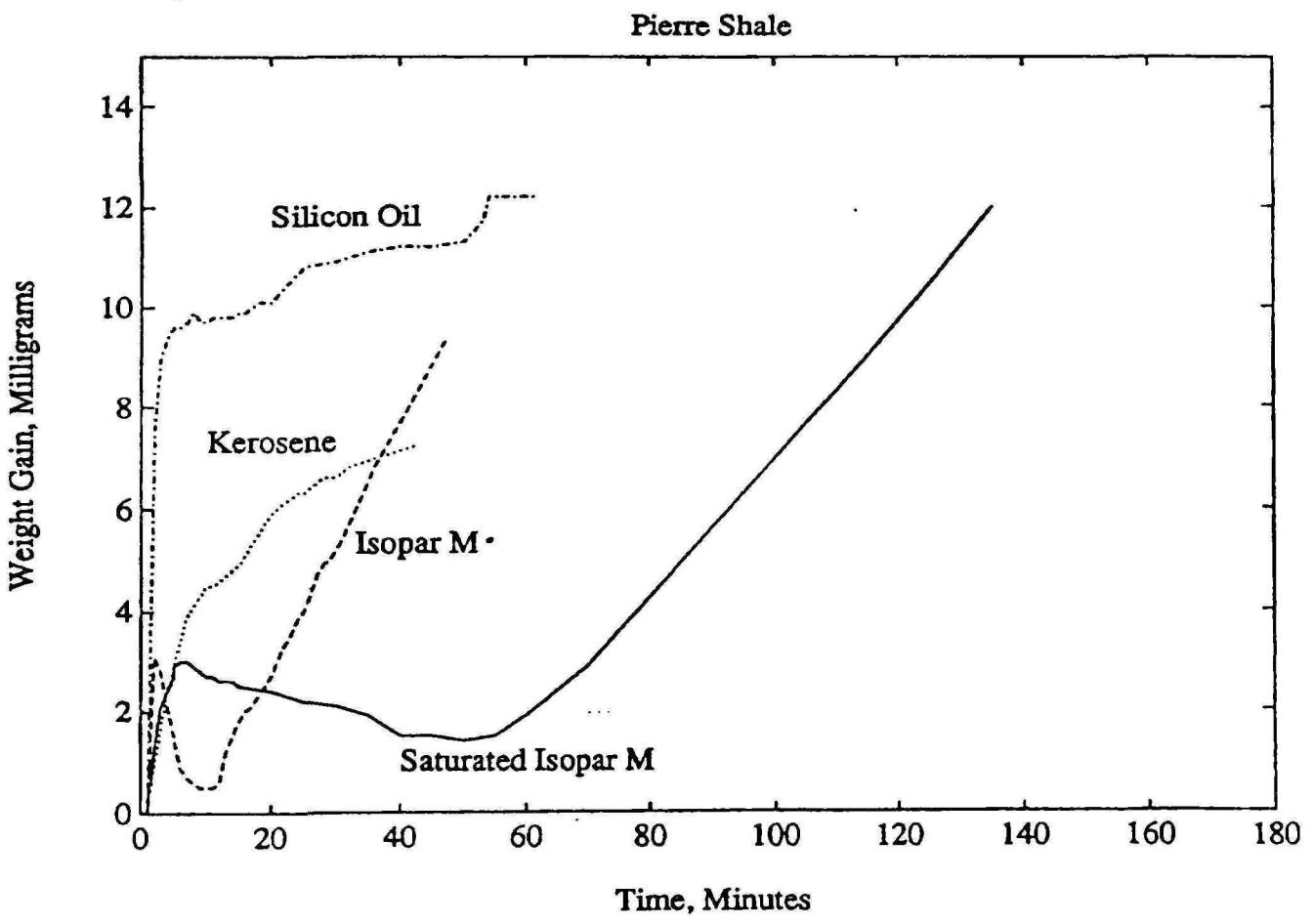


Figure 4.5 Buoyancy Changes of Shale (Adisoemarta et al., 1995)

The conclusion so far is that for the 100 minutes requirement for the sample to be in fluid before the next electromagnetic measurement, the saturated isopar M is the fluid of choice as the sample shrinkage is the smallest compared to other confinement fluids. For the long term storage requirement, the best fluid is silicon oil as the weight stops changing after 50 minutes. However the cost is prohibitive. Kerosene shows the weight change tapers off and flattens out eventually. Thus for practical purposes, kerosene is still a good long-term preservation fluid.

4.5.2 Electromagnetic Method

Another method that shows that fluids are exchanged from the sample into the preservation fluid is the analysis of the electromagnetic properties of the preservation fluid itself.

Figure 4.6 shows the change in conductivity of the preservation fluid after a Wellington shale has been immersed for 3 months. This long duration testing was executed to decide whether saturated Isopar M oil is a good long-term sample preservation fluid. As can be seen, the conductivity of the original fluid was around zero, and slightly increased at the higher frequency end due to impurities in the deionized water used to saturate the oil. The fluid that was in contact with the Wellington shale showed a huge increase, at the high frequency end, in conductivity. This conductivity increase can be attributed to ions that moved out of the pore space into the preservation fluid. Unfortunately no ion-analysis was done on this fluid to determine exactly what specific ion moved into the fluid.

Figure 4.7 shows the change in the dielectric constant of the preservation fluid. The clean fluid has a dielectric constant of around 2.25 and peaks at 2.44. The fluid that contained the shale sample showed a noticeable increase and peaked at 2.86. As the dielectric constant contrast between oil and water is 2 to 80, it can be concluded that the amount of water in the preservation fluid increased; hence, the amount of pore water in the sample decreased, and the sample properties could not be assumed to be the same as before the immersion.

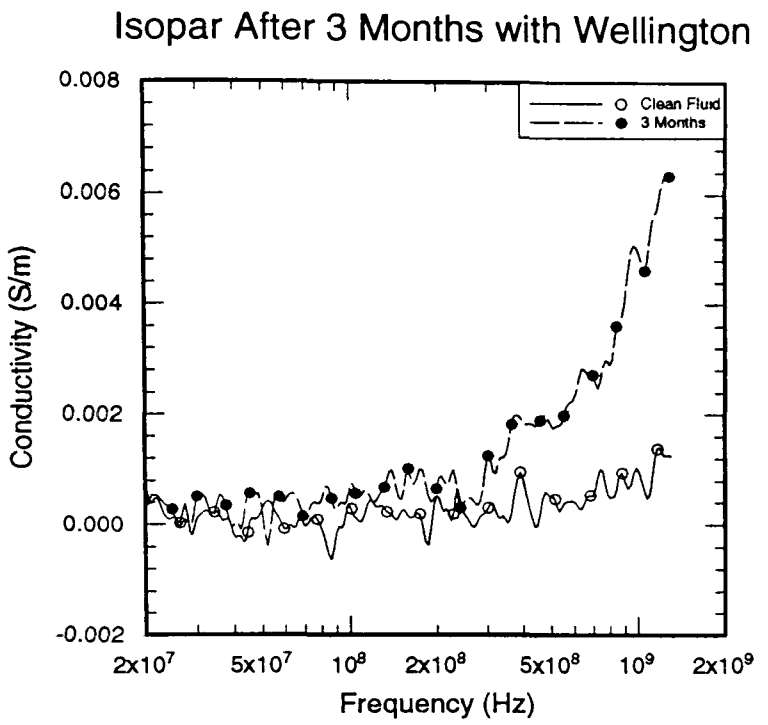


Figure 4.6 Conductivity Changes After Shale Immersion

Figure 4.8 shows the dissipation factor changes after the shale sample immersion. As the fluid is more conductive, more energy is lost as heat. The medium, therefore, is more electrically lossy and reflected as an increase on its dissipation factor.

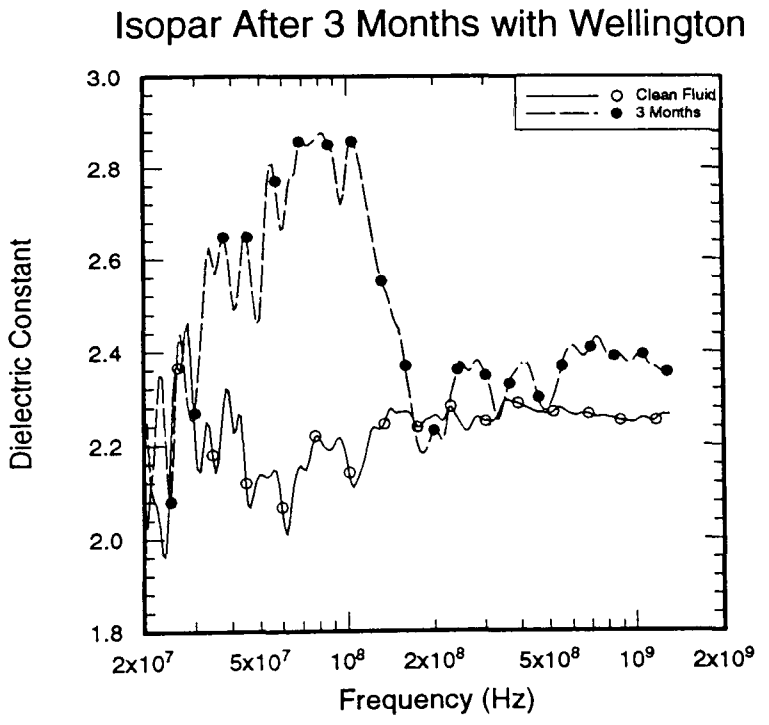


Figure 4.7 Dielectric Constant of Confining Fluid

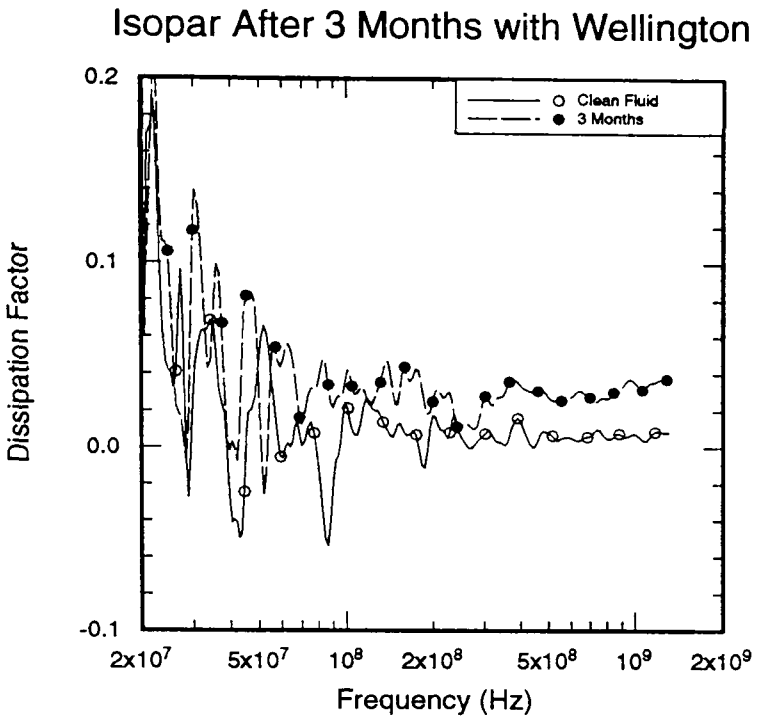


Figure 4.8 Dissipation Factor of Confining Fluid

The conclusion of this investigation is that there are fluid exchanges between pore water and the fluid for all preservation fluids that have been tested. Hence one should question the representativeness of a sample after its storage in fluid as the pore fluid will not have the same properties as the original one. The rate of fluid exchange can be reduced by pre--saturating the preservation fluid with deionized water. To avoid this exchange of pore fluid, especially for a long term sample storage, the non-fluid contact method should be utilized, such as sample waxing.

4.6 Air Entrapped In Shale (Adisoemarta, 1995)

One question that came up in this study was whether the shale sample was fully saturated with pore fluid or not before the experiment started. The partial saturation of shale will create a capillary effect that might significantly affect the experiment that is in progress (Forsans and Schmidt, 1994). For example, for the case of electrical measurement, this capillary effect will pull the preservation fluid into the sample and mask the actual changes of electrical resistance of the sample.

An experiment with Wellington shale was done by exposing the sample to air for a prolonged time to evaporate the pore water while the resistivity and the acoustic travel time across the sample were recorded. Figure 4.9 shows the measurement setup that uses a pulse

generator and a digitizing oscilloscope for the acoustic travel time, and a signal generator and voltmeter for the resistivity measurement. To ensure that no ionic buildup (also called "contact resistance") occurs at the electrode sample interface, the signal generator is set at 20 kHz. The detail of the electrical and computer hookup is shown in Figure 4.10 which illustrates that ambient humidity, ambient temperature, and sample length are also recorded through a multiplexer box, and the computer that automates the data acquisition process to ensure that the data will be recorded in a relatively fast pace (every 5 seconds) and error free.

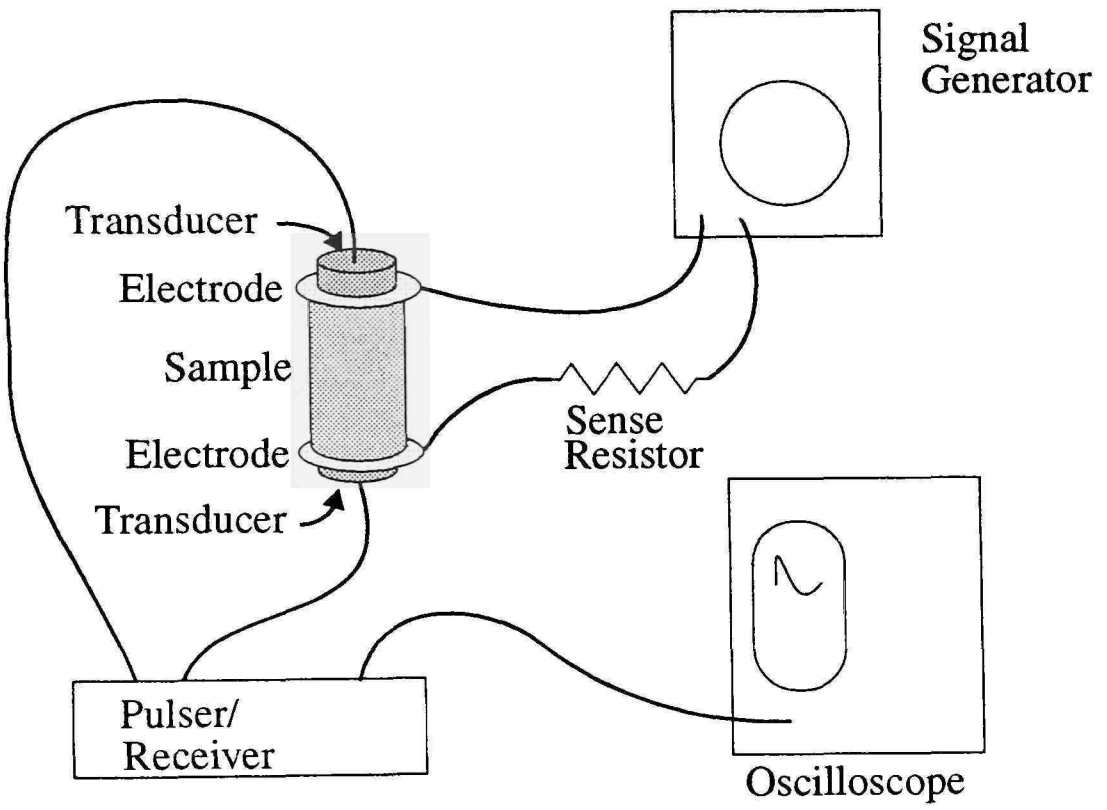


Figure 4.9 Acoustic and Resistivity Measurement Setup

The result of this experiment is shown on Figure 4.11. This plot shows 4 (four) regions with different slopes of either the sample resistivity or the acoustic travel time.

Ceramic drying theory by Keey (1991) states that as soon as the fully saturated sample is exposed to air, there will be pore water evaporation at the sample surface with the rate of evaporation being less than the rate of replenishment from the center of the core. This condition is designated as Condition I. The rate of replenishment from the center of the core will drop with time as there will be less water available, and this will create the condition II, where the rate of evaporation is larger than the rate of replenishment. As the amount of pore water diminishes, void space starts to grow from the sample surface. Condition III

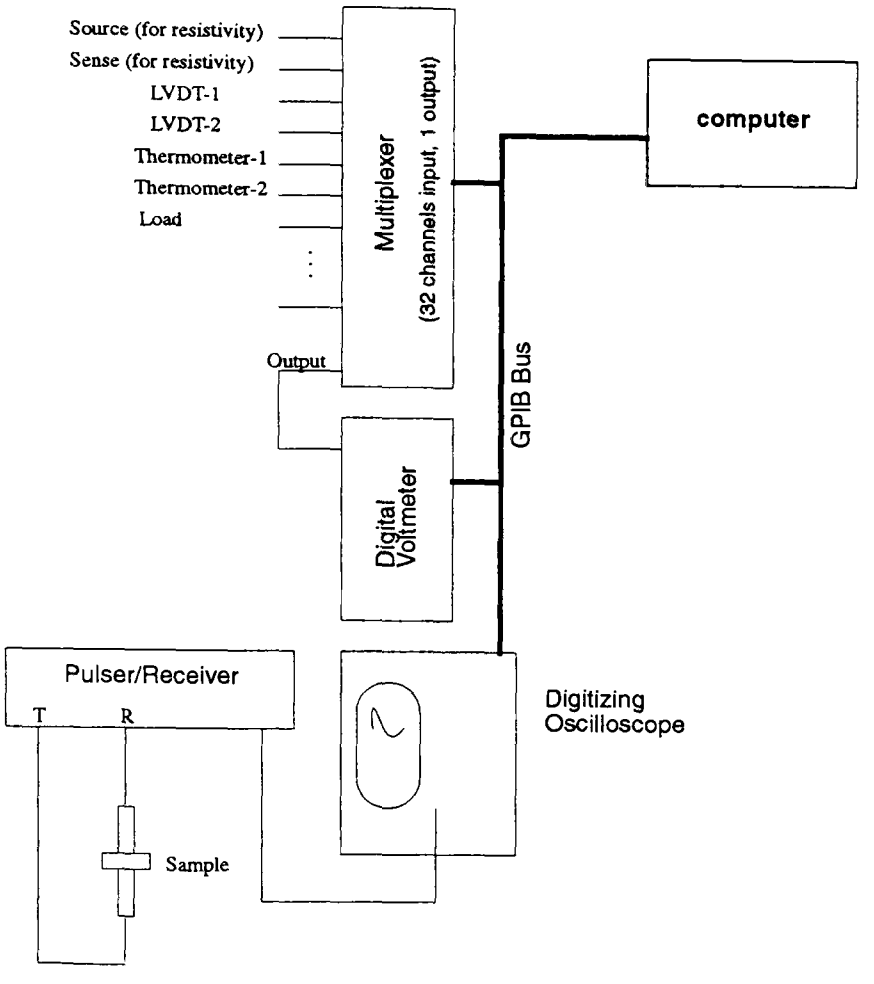


Figure 4.10 Electrical and Computer Setup for the Acoustic and Resistivity Measurement

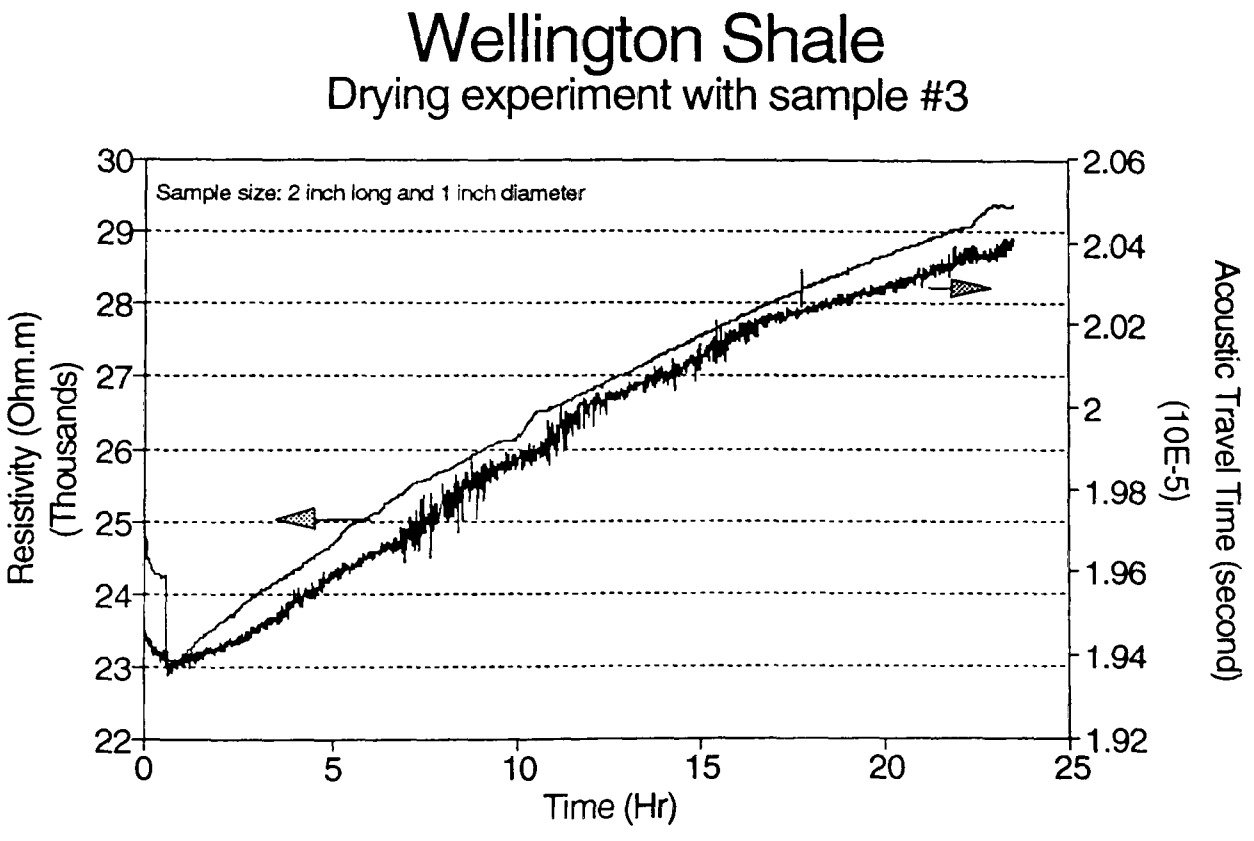


Figure 4.11 Resistivity and Acoustic Travel Time as the Sample Is Drying Out.

is when the void space reached the center of the core and as the core is now completely partially saturated, the rate of replenishment is even lower than the previous condition. The equilibrium in water saturation condition of the sample will be reached after all movable pore water has evaporated, and this is designated as Condition IV. The relation between each condition and time is shown schematically in Figure 4.12.

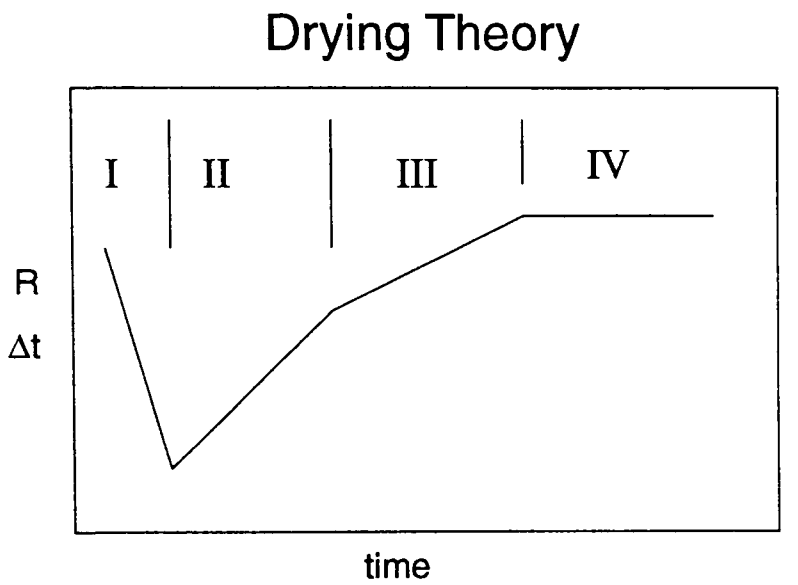


Figure 4.12 Sample Drying Conditions

An unsaturated sample will not exhibit all the regions, according to the theory because it will start directly at Condition II, bypassing Condition I, as there are air pockets that obstruct the pore water movement to replenish the water evaporated at the sample surface.

Only one shale sample out of three experiments show this behavior. Further testing needs to be done to verify the validity of this technique, as currently there is no knowledge to confirm whether the other two samples already have void space in the pore space before the testing or if the void space is due to other measurement artifacts, such as the use of an acoustic gel to make a good contact of the acoustic transducer or a sample surface that is not smooth and/or perfectly parallel.

In conclusion, this result shows that this acoustic/electric method potentially can be used to check whether new drilled core samples from the well site are fully saturated or not, but this method needs further investigation for confirmation.

CHAPTER V

ELECTROMAGNETIC MEASUREMENTS

This chapter will describe the experimental procedures in electromagnetic measurement that are used in this research and will include discussion on error sources, measurement equipment, reference materials, scope of research in frequency, and several results from shale samples.

5.1 Error Sources

Olhoeft (1981) discusses in detail several error sources in typical electromagnetic measurements either on dry or wet samples. In dry sample measurements, errors occur due to current leakage around the sample through the sample holder, cable coupling, fringing effect, and instrument drift. In wet samples, the above error sources can occur along with errors from current leakage due to wet sample surface, contact impedance between the electrodes and the sample, and chemical reaction between sample and sample holder.

The cable coupling errors (due to capacitive and inductive affect on the cables) are eliminated by using current driven shielded cable setup where the shield will have a current of the same magnitude but in the opposite direction than the signal, thus cancelling the inductive effect. This shielded cable also eliminates the capacitive interference between cables. Fringing effect is minimized by using samples as thin as possible. Contact impedance error, between the electrodes and the sample, is minimized by using a four-terminal setup where the potential electrode is located outside the charge build-up, and also by using a potential electrode with a high input impedance input so no significant current flows through the potential electrode to the sample. Chemical reactions between sample and sample holder are minimized by using inert sample holders (plexyglass), and non-reacting preservation fluid (to keep the moisture in the sample from drying out during the measurements).

The last error source, the instrument noise and drift, are handled by averaging several consecutive measurements and comparing daily readings against several reference materials, respectively.

5.2 Scope of Research

Each shale sample in this research will be measured for its electromagnetic properties in the range from 5 Hz up to 1.3 GHz ($1.3x10^9$ Hz) using two different measurement setups, as shown in Figure 5.1. Also shown in the figure are the commercially available logging tools; thus it would be easy to implement the results of this study to the actual well log reading. The width of the frequency span of this study, which is about 7.5 orders of magnitude in frequency ($5x10^1$ to $1.3x10^9$ Hz) encompasses almost half of the current techniques in electromagnetic measurement, which is 17 orders of magnitude (10^{-6} to 10^{11} Hz) as reported by Olhoeft (1981).

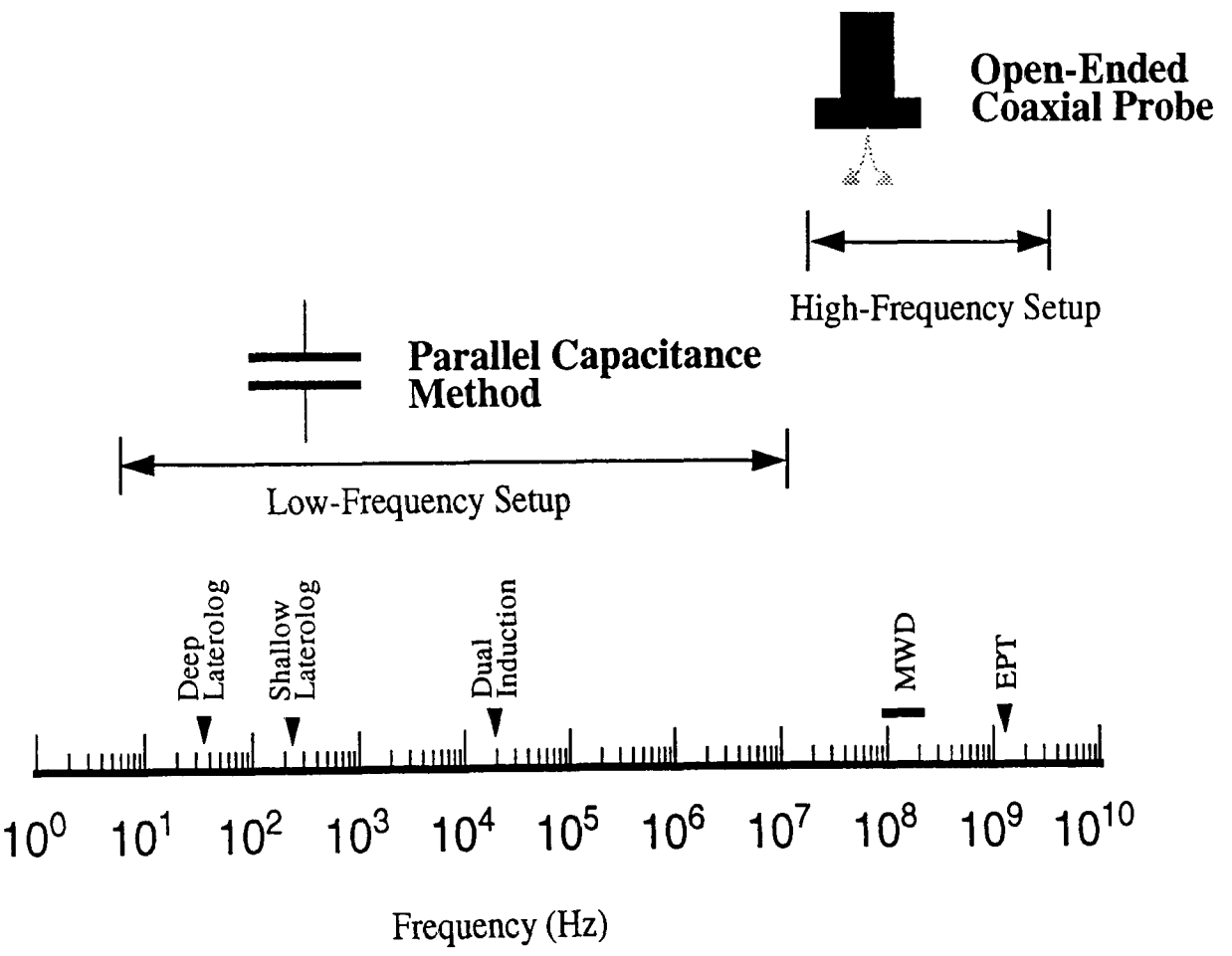


Figure 5.1 Frequency Span of the Measurement Equipment and Current Commercial Logging Tool Frequencies

5.3 Measurement Apparatus

The complex electrical parameters of the sample were measured over two frequency ranges using two different measurement techniques.

5.3.1 Low Frequency

The low frequency range, from 5 Hz to 12 MHz (1.2×10^7 Hz), is measured using an HP 4192A impedance analyzer in conjunction with a parallel-plate measurement technique as shown schematically in Figure 5.2.

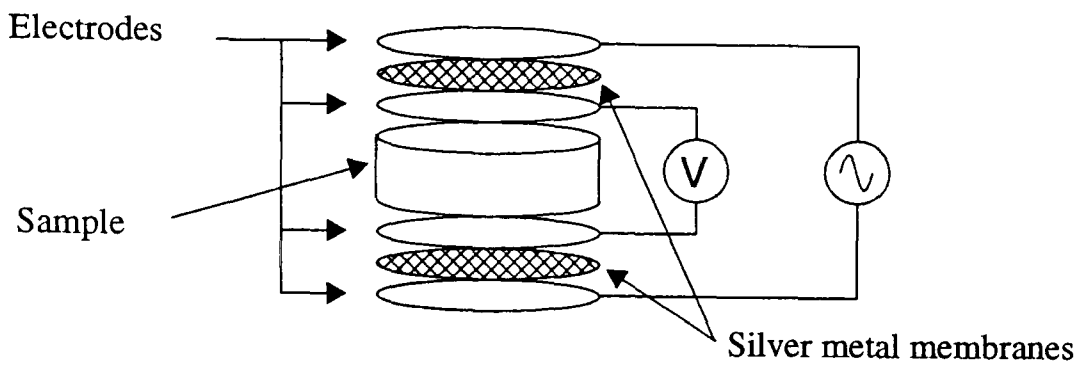


Figure 5.2 Parallel-plate Measurement Technique

This setup is the 4-port parallel-plate technique in which the current and voltage measurement electrodes are separated by a thin porous conductive plate. The electrodes are gold-palladium coated brass porous plates, and the separator plates are Poretics^{TM} silver metal membranes, a product of Osmonics.

In the beginning of the research, the 2-port parallel-plate method was used instead, using the HP16451A Dielectric Test Fixture, but due to induced DC current that was generated by the shale sample during measurement, the 4-port was then implemented through custom built cabling that also preserves the cable shielding feature of the 2-port fixture.

The analyzer is controlled via an IEEE-488 (GPIB/HPIB) bus from a microcomputer. Software has been written to acquire the measurements. This allows the researchers to acquire data with fine frequency resolution and reduce operator error, as the equipment readings will be saved directly to the storage media, for further processing. A fixture has been built for shale measurements submerged in preservation fluid. This fixture will improve the data because the sample will keep its moisture since there is no air contacting the sample to dry it out.

5.3.2 High Frequency

The high frequency range starts at 20 MHz (2 x 10^7 Hz) and ends at 1.3 GHz (1.3 x 10^9 Hz). Measurements are made using an HP 8752A network analyzer. This instrument actually consists of two parts: the network analyzer and the display processor. An open-ended coaxial probe, HP 85070B, is used to determine the reflectivity, S^*_{11}, of the sample. This is converted to real and imaginary permittivity using the manufacturer's software, which incorporates an algorithm for correcting for geometric effects in the probe. Figure 5.3 shows schematically the open-ended measurement technique.

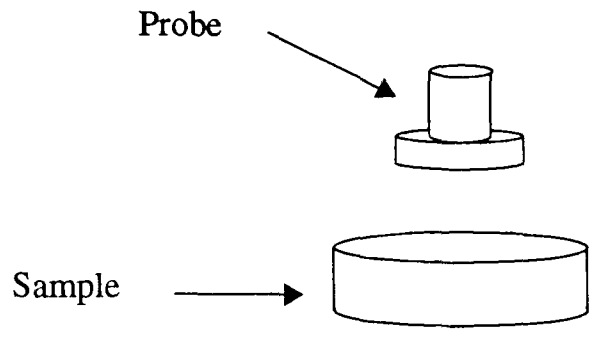


Figure 5.3 Open-ended Measurement

The instrument is calibrated by measuring three well-known dielectric mediums, also called *calibration standards*. The default calibration standards for this probe are air, a short circuit, and deionized water. This calibration standard is also called "Air/Short/Water" method. Other calibration standards for the instrument are "Load/Air/Short," where a 50 ohm coaxial load is substituted for water, and "User Defined," where three known standards can be described and and their electrical properties measured (HP, 1993). The "Air/-Short/Water" calibration process is always done after the instrument has been on for at least 30 minutes, thus ensuring it has reached its operating temperature, and after around 60 measurements. There is a bug in the Windows^{TM} version 3.1 operating system that slowly leaks memory. After around 60 measurements the computer loses all the memory space and this condition makes the computer run very sluggish; hence a reboot is necessary, and by rebooting, the instrument loses its calibration setup.

All shale dielectric measurements were done by taking 5 consecutive readings, and the averaged value is the one reported herein.

5.4 Calibration Check

To ensure a consistent reading on the day-to-day measurements and to detect any drifts that might occur from the measurement equipment, a set of reference materials are measured before and after the actual sample measurement. The reference materials are as follows:

- light plastic and heavy brass for the balance, for weight measurement
- Alcryn^{TM} (a thermoset synthetic rubber, a product of Dupont) for the low-frequency equipment,
- deionized water for the high-frequency equipment.

Figure 5.4 shows the complex electrical properties of Alcryn as a function of frequency. Alcryn was selected as a reference material because at 1 MHz, it has a high dielectric constant value, near that of shale, and the material is not hazardous.

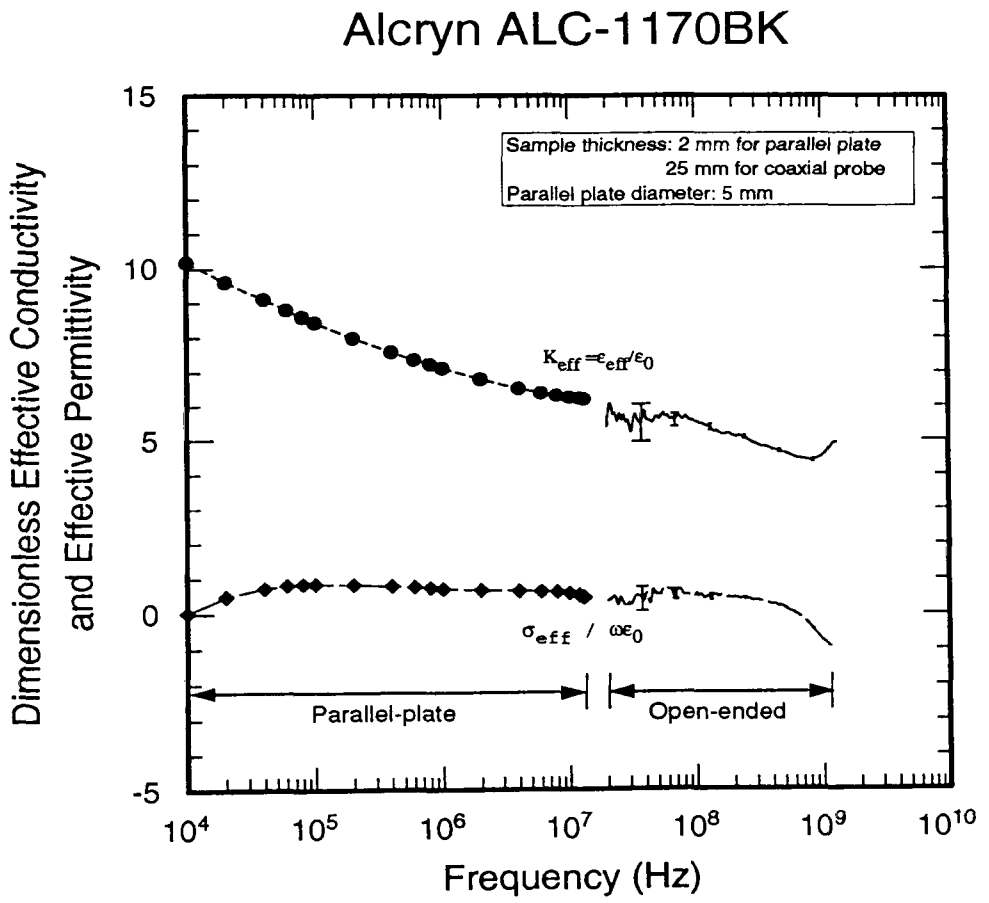


Figure 5.4 Complex Electrical Properties of Alcryn as a Function of Frequency.

The transition between the parallel plate and the open-ended coaxial probe measurements is smooth, although the probe data are increasingly noisy below 200 MHz as

shown by bigger error bars. Alcryn rubber is a relatively non-conductive material. Probe data are smoothed with a 5-point unweighted moving average.

Figure 5.5 shows the dimensionless effective permittivity (i.e. effective dielectric constant, ε_{eff}) vs. frequency of deionized water measured with the parallel-plate fixture and the open-ended coaxial probe. Also shown on the plot is the dielectric constant formula presented by Hasted(1973). Symbols are plotted for all data from the parallel-plate measurements, but not for the probe measurements since the data density is too high (201).

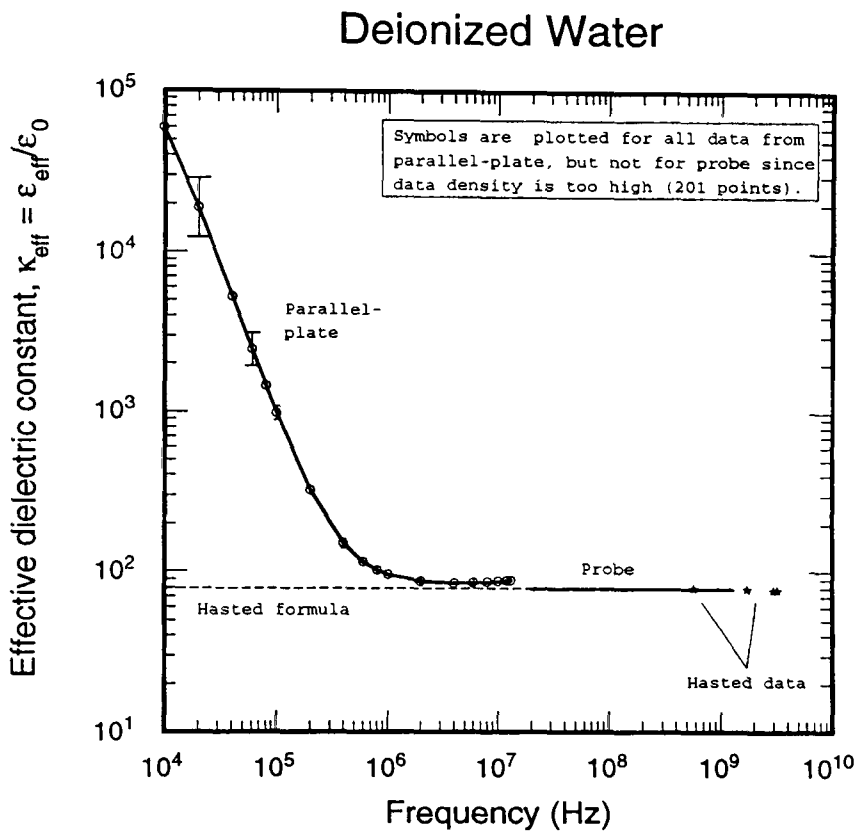


Figure 5.5 Effective Dielectric Constant of Deionized Water

5.5 Comparison Against Published Results

To ensure that the equipment is working properly, methanol and brines have been measured for their electrical properties and compared against their published values.

Figure 5.6 shows the permittivity (both the real and imaginary part) of methanol measured by Jordan et al. (1978), overlaid with the measurement of this dissertation. The dissertation measurements agree with the published data, suggesting that the high-frequency open-ended coaxial probe is working properly. Accuracy of the probe measurement is

demonstrated over the frequency range of 20 MHz to 1.3 GHz, although the manufacturers design limit is > 200 MHz.

Figure 5.7 shows the effective conductivity of NaCl and KCl brines at 2000 ppm concentration, at ambient (60°F) temperature, measured with the open-ended coaxial probe. Also shown on the plot is the conductivity of NaCl and KCl taken from Charts Gen-8 and Gen-9 of the *Log Interpretation Charts* (Schlumberger, 1995).

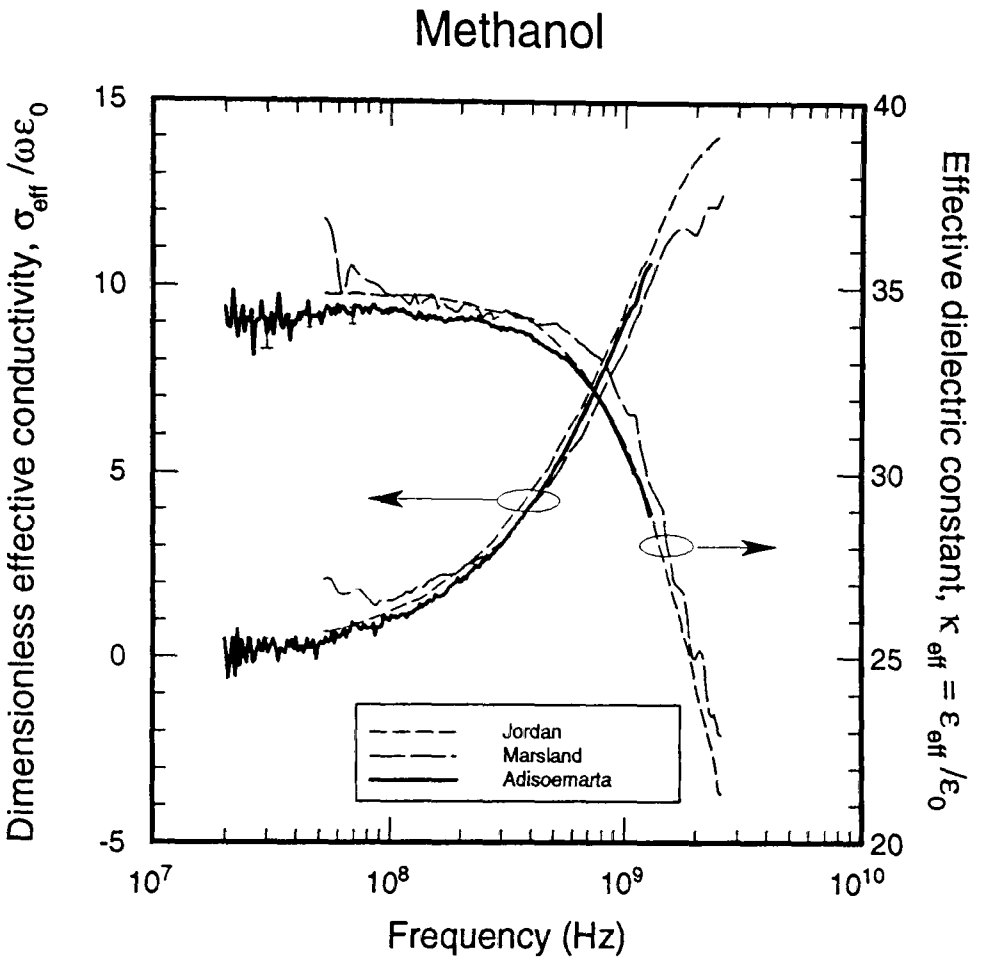


Figure 5.6 Complex Electrical Properties of Methanol

5.6 Varying the Sample Water Content

The main objective of this dissertation is to measure the shale sample's complex dielectric properties as a function of water content; hence, the water content has to be modified in a controlled scheme for each sample. There are several ways that have been used for this research to change the amount of water in the sample, namely the desiccator, electrophoresis, and air drying method.

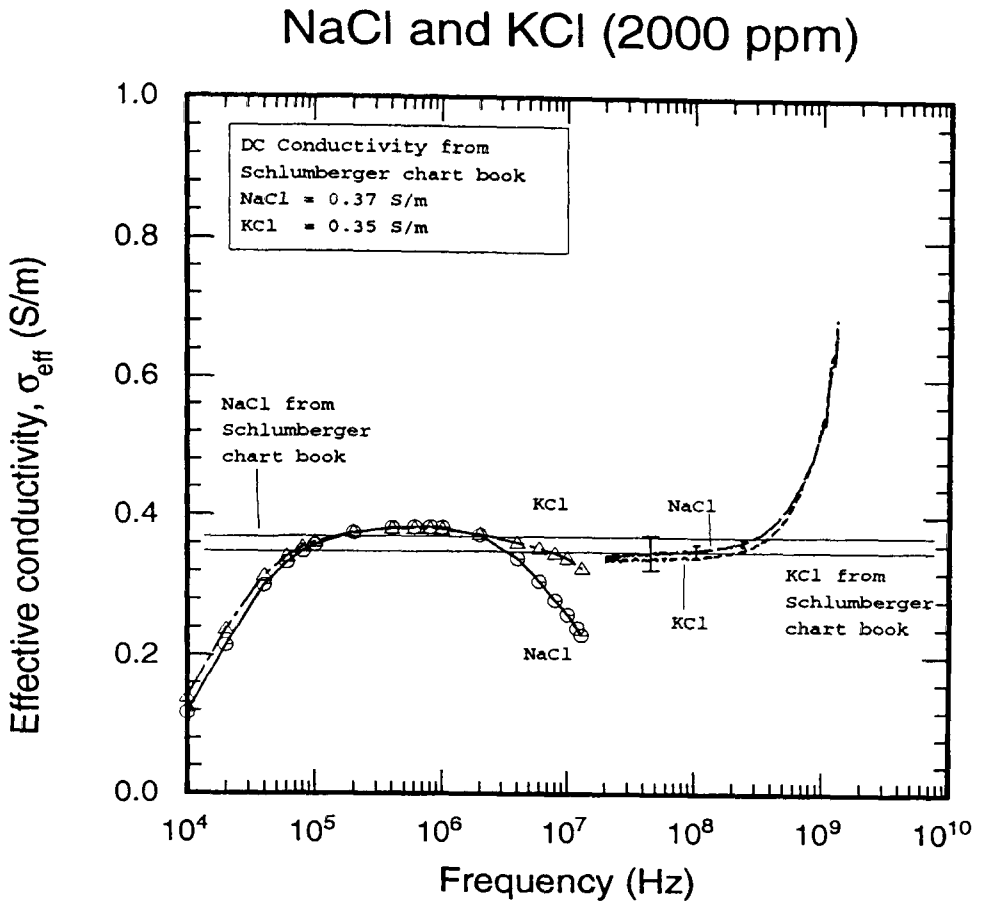


Figure 5.7 Effective Conductivity of NaCl and KCl

5.6.1 The Desiccator Method

Figure 5.8 shows a plot of the complex electrical properties of a shale for the complete frequency range. The sample is a Pierre shale that was measured at 4 (four) different water contents after being kept for several days inside various desiccators that had the particular water activities indicated.

The fact that the two frequency ranges were measured using two completely different methods makes the splicing of the spectra difficult. After improving the measurement fixture for the low frequency setup, the two ranges were combined in a single, continuous plot. A gap exists on the plot since the upper limit of the low-frequency equipment is 13 MHz while the high-frequency equipment starts at 20 MHz. The fact that the two completely different measurement methods, the parallel-plate for the low frequency range and the open-ended coaxial probe for the high-frequency range, show approximately the same conductivity trend with frequency confirms the accuracy of the both measurements to some degree.

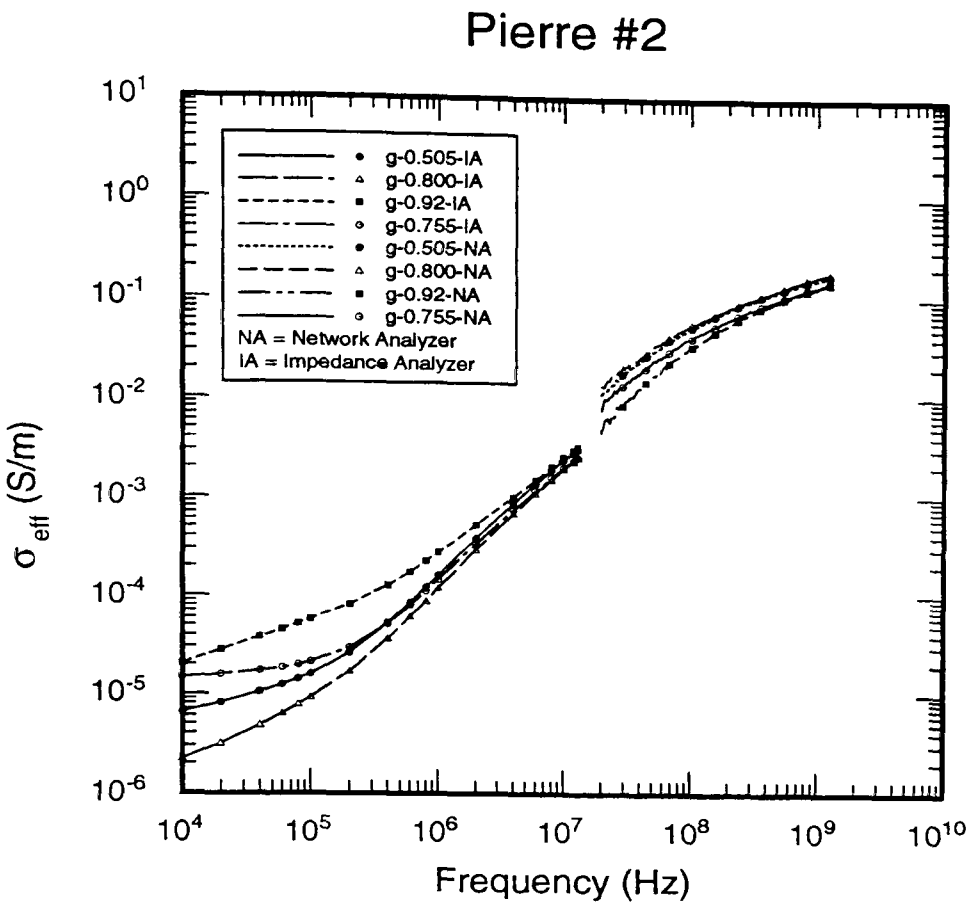


Figure 5.8 Effective Conductivity of Pierre Shale as a Function of Water Content

The author has been unable to explain the fact that on the low-frequency range the effective conductivity increases with increasing water content, but on the high-frequency range, the effective conductivity drops with the increase of water content. The author acquired another instrument that will work on that frequency gap to get more insight on this fact, but, unfortunately, the instrument arrived malfunctioning.

5.6.2 The Electro-osmosis Experiment

One method to change water content of shale is to impress a direct electrical voltage on the sample that will move the water to one side of the sample. This method is called the electro-osmosis method (Rose, 1980). The theory behind this method is that the cations (positively charged ions) and anions (negatively charged ions) will move to the charged electrodes to satisfy the system's neutrality. So cations will move towards the anode and the anions will move towards the cathode. As the anions are in the pore water, the movement of the anions will also bring the pore water to the cathode side. On the other hand, the cations are on the clay platelets, so they will not move. After the sample is impressed

with the voltage for a period of time, the sample is cut laterally to preserve the water content of each particular location. The individual slices are then analyzed for water content, Brinell hardness index, and the complex electrical parameters at various frequencies. This method is described schematically in Figure 5.9.

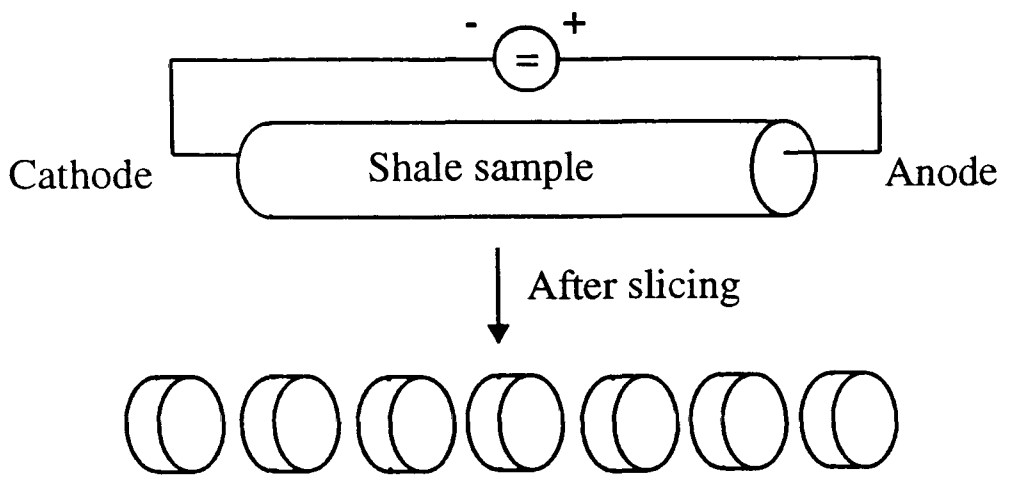


Figure 5.9 Electro-osmosis Method

The samples for this experiment are two Pierre shales, designated as Sample H and Sample I. These shale samples were received from Shell Bellaire Research Center in Houston, where researchers from Shell conducted the electro-osmosis process and the Brinell hardness (BHN) measurement.

Figure 5.10 shows the electrical current across each sample as a function of time. It can be seen that the current decreases with time as the ion buildup at the electrode reduces the conductivity of the system.

Water content and Brinell hardness number for each slice of Sample H is shown in Figure 5.11 and Figure 5.12 shows the measurements for Sample I. As can be seen, both samples show that water is more concentrated at the cathode end and decreases towards the anode end, as expected from the electro-osmosis method, and as the sample gets drier, it gets stronger and harder, as indicated by the increasing BHN towards the anode end.

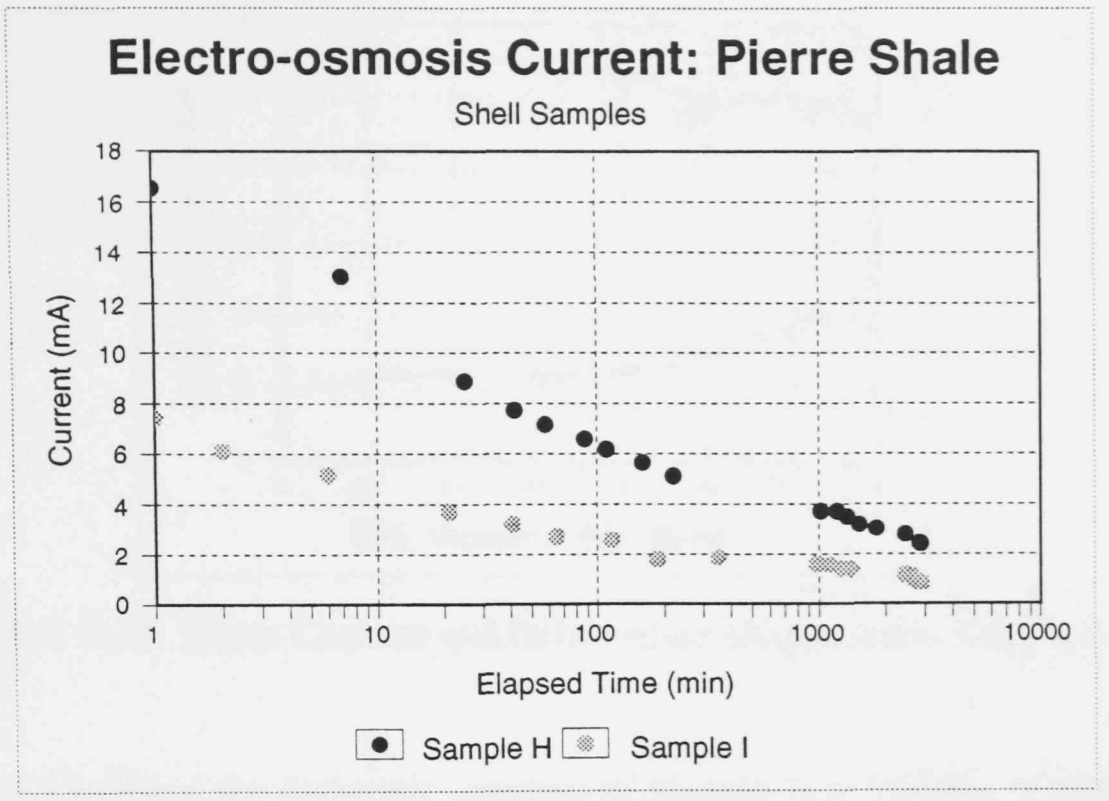


Figure 5.10 Electro-osmosis Current

Even though Figure 5.11 shows the water content and BHN of slice H10, because the sample broke off during sample handling, there are no data presented for the electrical properties.

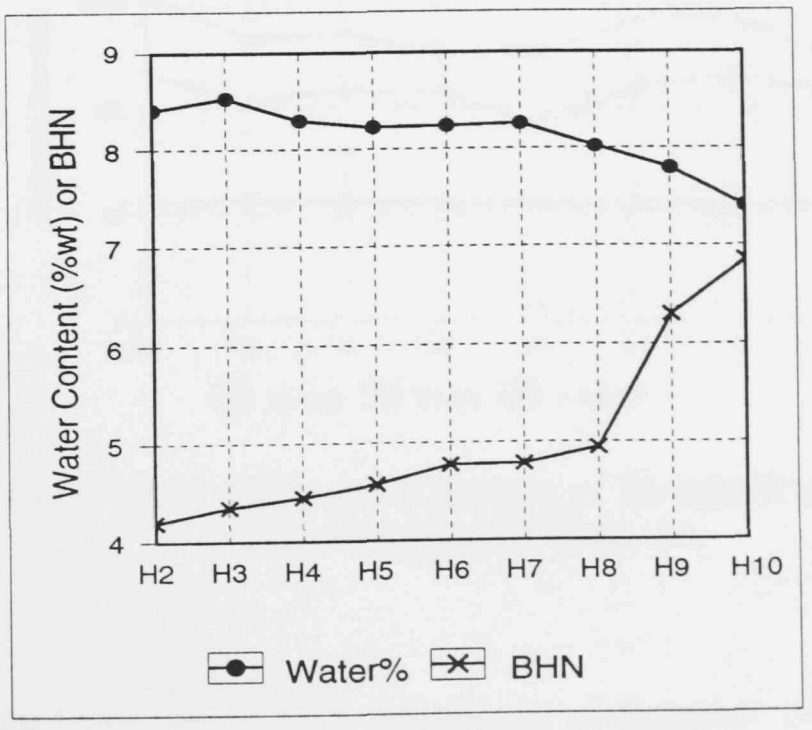


Figure 5.11 Water Content and BHN versus Distance for Sample H

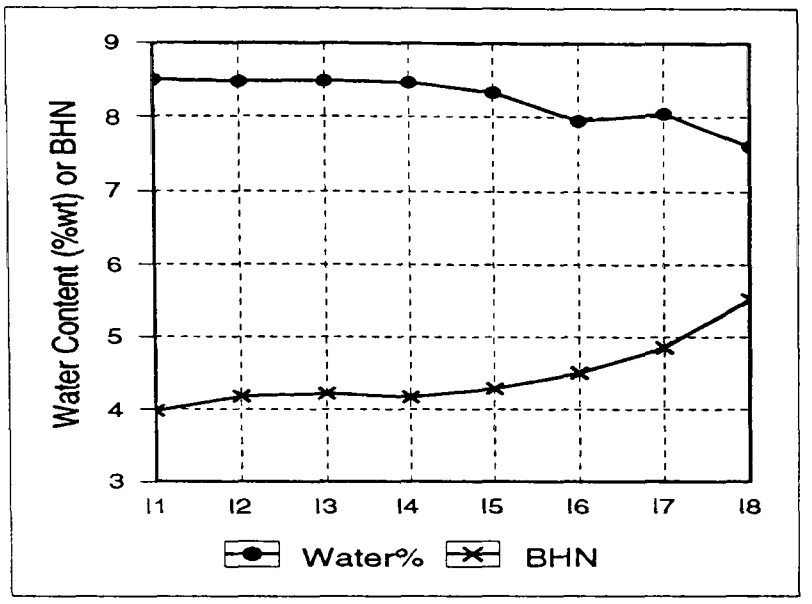


Figure 5.12 Water Content and BHN versus Distance for Sample I

Figure 5.13 shows the dielectric constant of Sample H at 20 kHz, 2 MHz and 1.1 GHz (those are the Dual Induction, MWD tool, and EPT tool frequencies, respectively) as a function of lateral distance from the cathode to the anode.

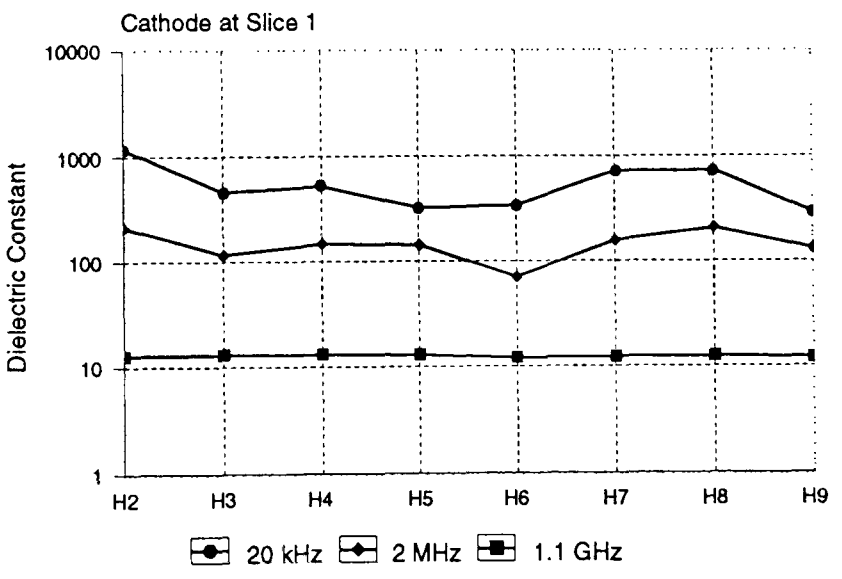


Figure 5.13 Dielectric Constant of Sample H at Three Logging Frequencies

As can be seen from Figure 5.13, the change of dielectric constant is more pronounced at low-frequency than high-frequency. For example, the increase in water content at slice H3 can be seen clearly at slice H4 at 20 kHz, and slice H5 at 2 MHz reading;

a smaller change can be seen at slice H4 at the 1.1 GHz reading. Another example is the higher water content reading at slice H7 that can be seen on slice H7 and H8 at 20 kHz and slice H8 on the 2 MHz reading. This increase in water content is almost undetectable on the 1.1 GHz dielectric constant reading.

Figure 5.14 shows the dielectric constant response of Sample I at the same three logging frequencies.

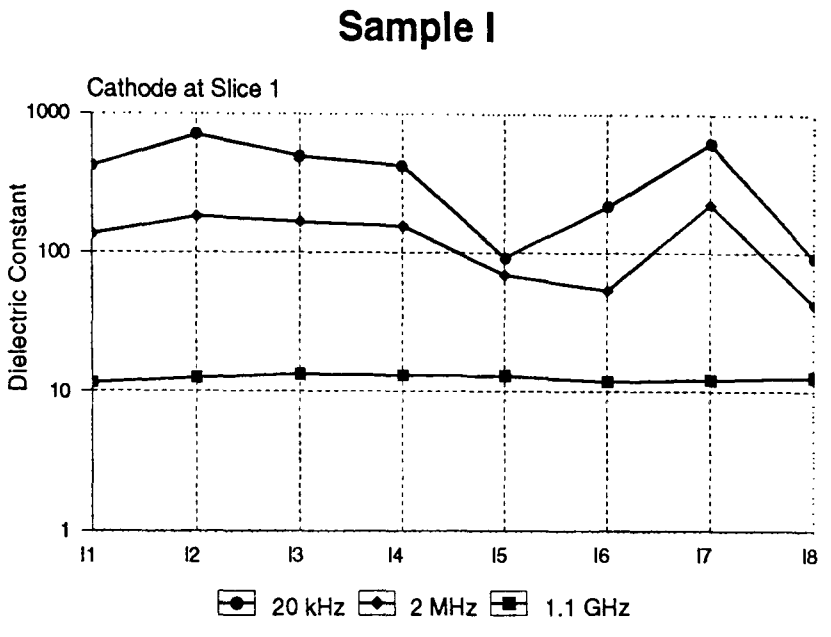


Figure 5.14 Dielectric Constant of Sample I at
Three Logging Frequencies

As for sample H, sample I shows that the effect of water content is more pronounced at the lower frequencies. The drop in water content at slice I6 can be seen on the 20 kHz and 2 MHz measurements at slices I5 and I6, respectively, but there is almost no change at slice I6 on the 1.1 GHz reading. The increase in water content at slice I7 can be observed clearly at the two lower frequencies, but again there is almost no change in the high-frequency, 1.1 GHz, reading.

Both samples show that the dielectric constant changes with water content, and the change in dielectric constant is more pronounced in the lower frequency range.

Figures 5.15, 5.16 and 5.17 show the complex electrical properties conductivity (G), susceptivity (B), and dissipation factor (D) for sample H at the three logging frequencies (20 kHz, 2 MHz, and 1.1 GHz).

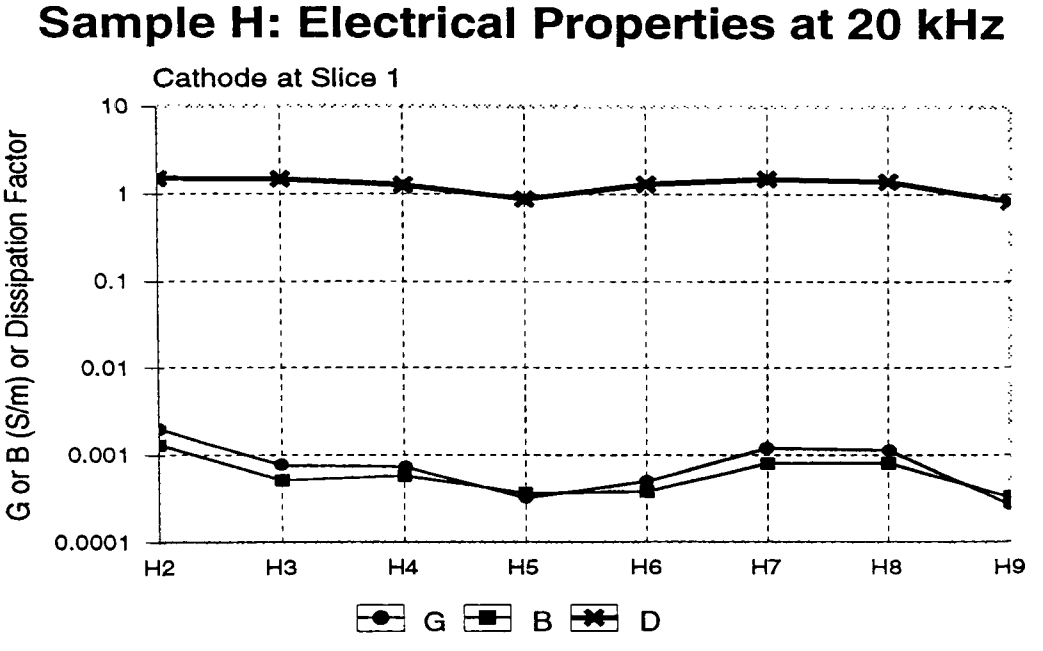


Figure 5.15 Electrical Properties of Sample H at 20 kHz

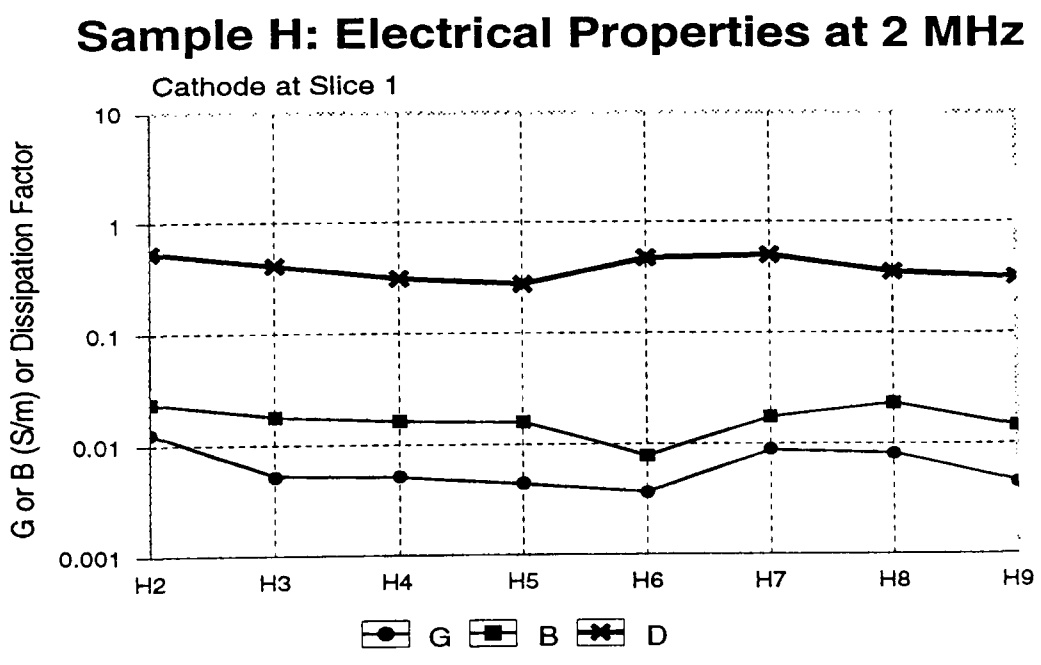


Figure 5.16 Electrical Properties of Sample H at 2 MHz

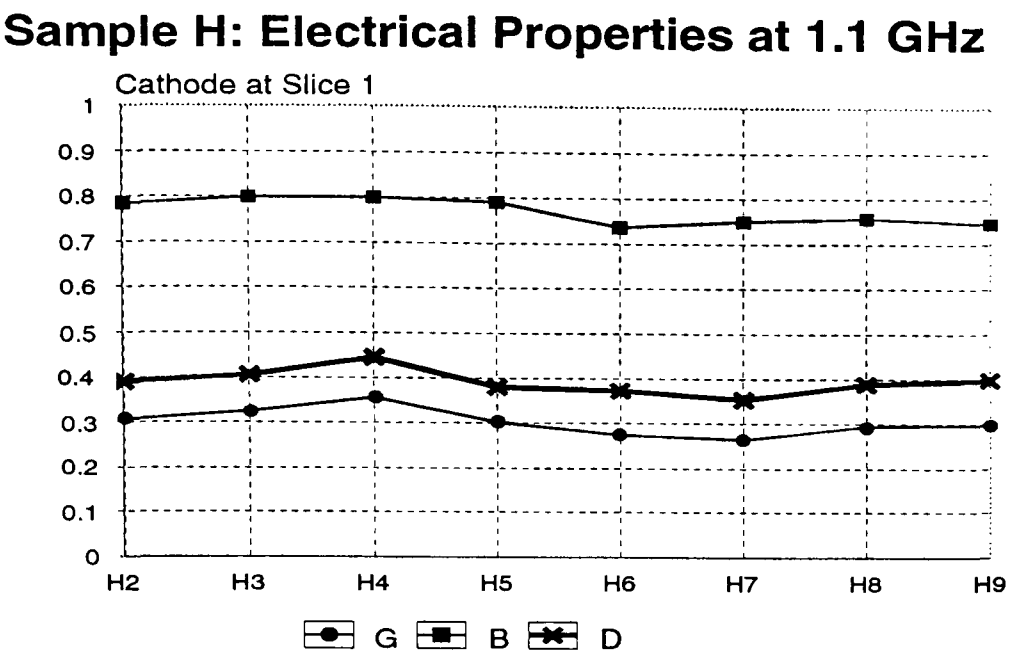


Figure 5.17 Electrical Properties of Sample H at 1.1 GHz

For 20 kHz, Figure 5.15 shows that conductivity (G) and susceptivity (B) increase as water content increases. For example, the increase of water content at slice H3 can be seen on the conductivity and susceptivity at slice H4. When water content drops at slice H5, the effect on electrical properties can be seen at the same location, and when water content rises again at slice H7, the increase is reflected in the electrical properties at the same location. The dissipation factor also changes as the water content changes. The general trend is that conductivity and susceptivity are decreasing from the cathode end to the anode, as is water content.

For 2 MHz, Figure 5.16 shows that the drop of water content at slice H5 is detected at slice H6 on both the conductivity and susceptivity. The water content increase at slice H7 can be seen on conductivity right at that slice and on susceptivity on slice H8. The dissipation factor is also reflecting the changing water content, as shown in slice H7 where water content is slightly increased, which is reflected in the slightly increasing dissipation factor.

For 1.1 GHz, Figure 5.17 shows that the increase of water content at H3 can be seen at slice H4, the drop of water content at H5 can be seen at H7, and the increase at H8 can be seen at H9. There is no clear trend of conductivity and susceptivity decreasing from the cathode to anode. The dissipation factor shows that the increase of water content at slice

H3 is reflected by an increase in dissipation factor at slice H3 and H4, the drop of water content in slice H5 is reflected at slice H, and the small increase of water content at slice H7 is reflected in dissipation factor at slice H8.

The conductivity, susceptivity and dissipation factor of Sample I at the three logging frequencies of 20 kHz, 2 MHz and 1.1 GHz are shown on Figures 5.18, 5.19, and 5.20.

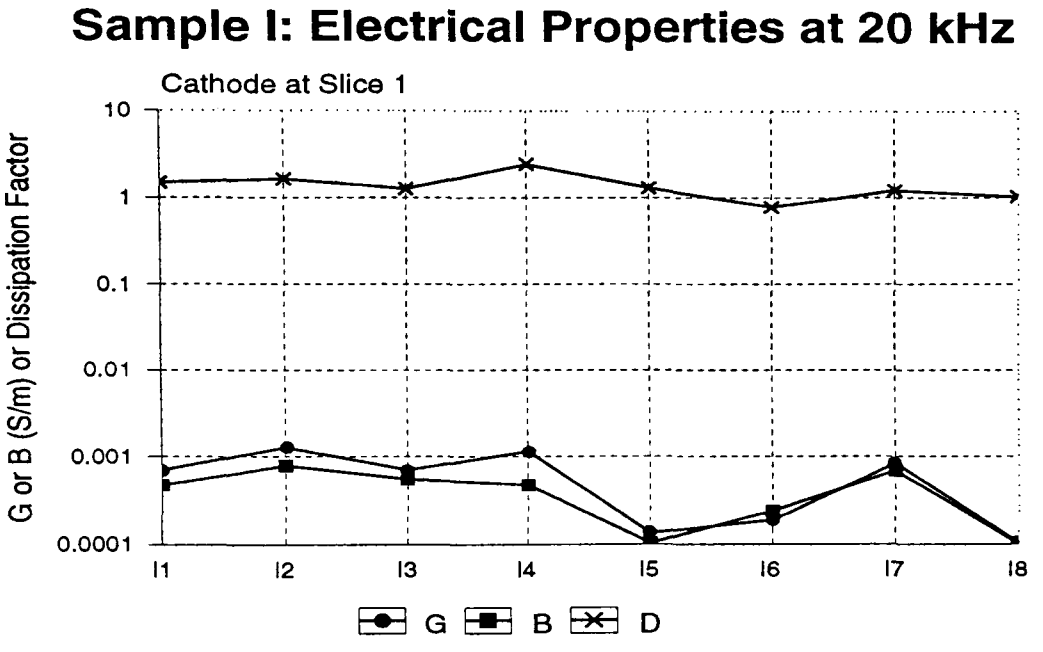


Figure 5.18 Electrical Properties of Sample I at 20 kHz

Sample I has a smooth decreasing water content, as shown in Figure 4.25, with two interesting locations, slice I6 and I7, that have lower and higher water content, respectively.

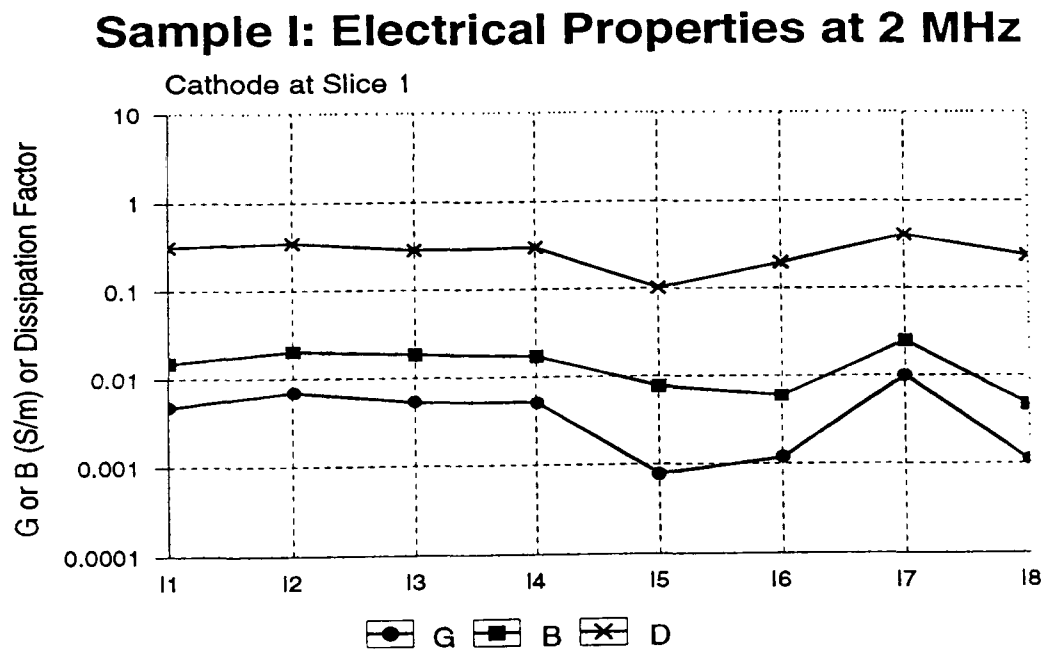


Figure 5.19 Electrical Properties of Sample I at 2 MHz

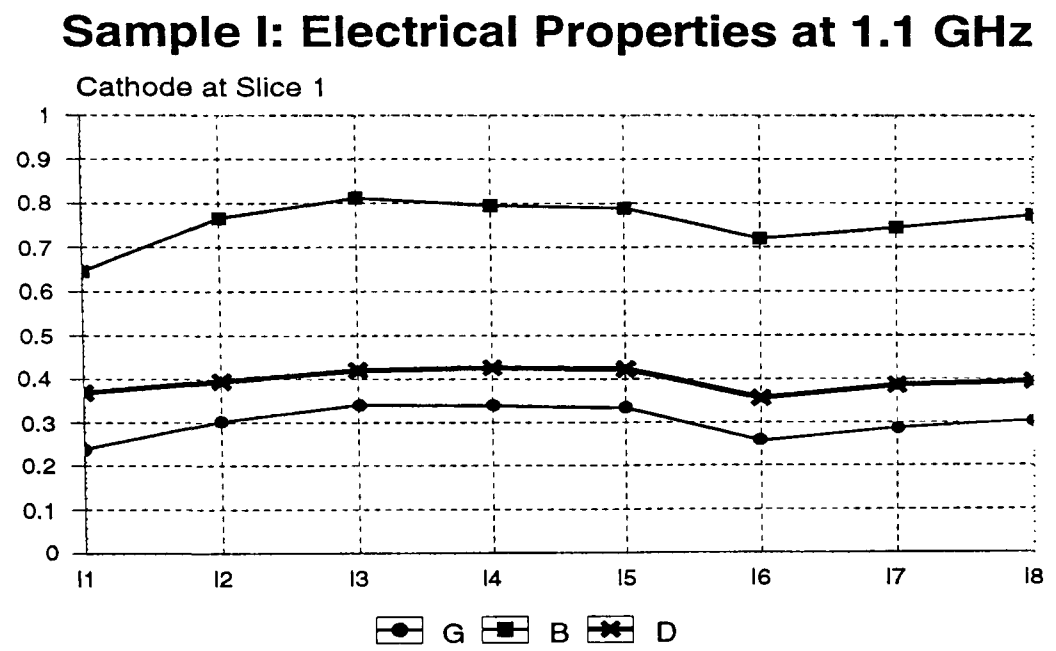


Figure 5.20 Electrical Properties of Sample I at 1.1 GHz

For 20 kHz, Figure 5.18 shows that the drop of water content at slice I6 is reflected on both conductivity and susceptivity at slice I5, with a corresponding drop in dissipation factor in slice I6. The increase of water content at slice I7 is reflected in increase of conductivity, susceptivity and dissipation factor in the same sample slice location.

For 2 MHz, Figure 5.19 shows that the drop of water content at location I6 is reflected in drop in conductivity at slice I5, susceptivity at slice 6, and dissipation factor at slice 5. The increase of water content at slice 7 is reflected consistently at that particular location for the electrical parameters.

For 1.1 GHz, Figure 5.20 shows that the drop of water content at slice I6 is reflected well in the same location for all electrical parameters. The increase of water content at slice I7 is reflected on slice I7 and I8.

Several results that have been observed from the electro-osmosis experiment are as follows:

- Water increases toward the cathode end as predicted
- The affect of a change in water content on conductivity, susceptivity and dissipation factor is more defined at the lower frequencies,
- The change of water content is not always reflected by a change of conductivity/susceptivity at that particular location, but by changes at neighboring samples.

5.6.3 The Air Evaporation Method

Another way to reduce the water content in a shale sample is to expose the sample to air for a while, letting a small amount of pore water at the sample edge evaporate, and then allow the water to redistribute evenly before another set of electromagnetic measurement is performed on that particular sample. A carefully arranged air exposure procedure has to be executed so that the amount of water remaining in the sample can be monitored in a controlled way.

The procedure exposes the sample to air for 5 minutes while the sample sits in an opened digital analytical balance, and then resaturates the sample for 2 hours while the sample is immersed in fluid before the electromagnetic measurement is taken on that particular sample. Figure 5.21 shows the timeline of one shale sample.

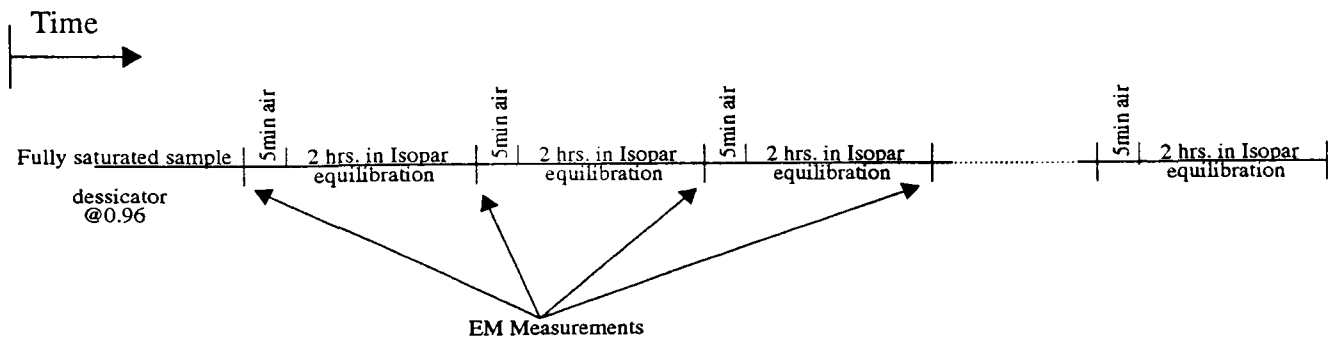


Figure 5.21 Experiment Procedure Timeline

As shown in Figure 5.21, a fully water saturated shale sample is taken out of a desiccator that has water activity of 0.96, the water activity of native Wellington shale, and then its electromagnetic properties are measured. This measurement is for the fully saturated condition. After this measurement is done, the sample is then exposed to air for 5 minutes in an opened digital balance. To re-equilibrate the sample to the new water saturation condition after the sample edges are exposed to air, the sample is immersed in inert fluid, Isopar, for two hours. This re-equilibration time has been determined from one test that shows the changes of electrical properties stop changing after around 90 minutes, as shown in Figure 5.22 Hence if the equilibration time is set for 120 minutes (2 hours), then it can be safely assumed that the water saturation has re-equilibrated completely. After the sample has

assumed the new equilibrium condition, another set of electromagnetic measurement is done. The sequence repeats again until the sample shows a visible crack on the sample surface that indicates air has entered the sample. As already mentioned in the error sources section, due to the low value of the dielectric constant and the non-conductive nature of air, even a thin gap of air will skew the measurement result, and hence the data will not be representative.

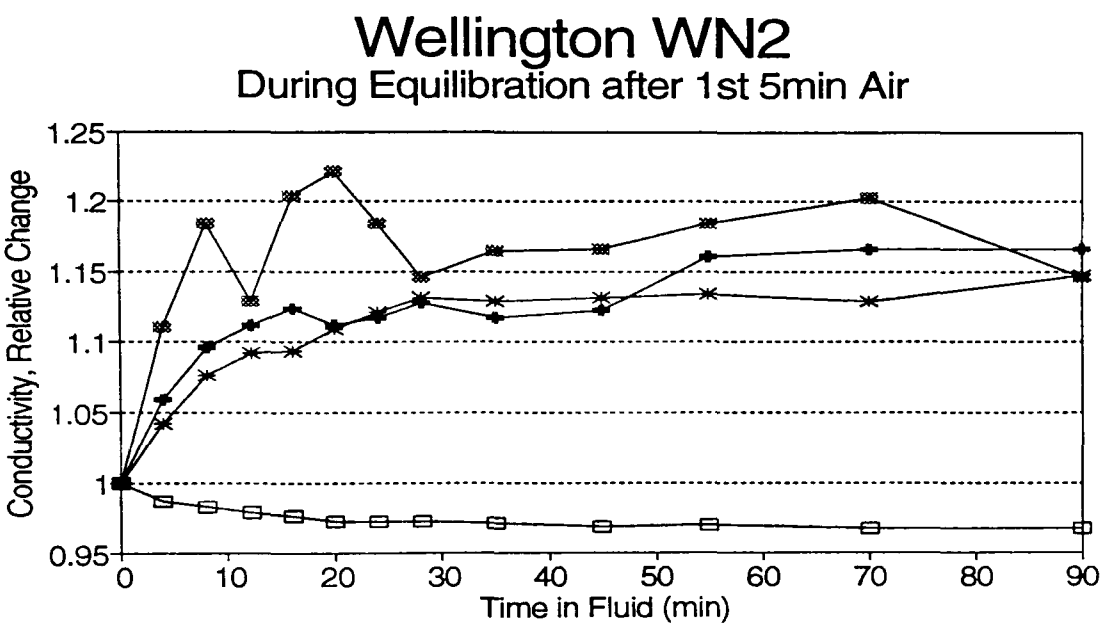


Figure 5.22 Relative Change of Conductivity at Various Frequencies as a Function of Time in Inert Fluid

The actual sample weight changes as a function of air exposure time in the digital balance for every measurement set are shown in Figure 5.23. The figure shows that sample weight has a constant rate of weight drop, which means the rate of evaporation is constant.

Figure 5.24 is a replot of the previous plot, but in this plot the end weight of the 5 minutes of air exposure is plotted against the cumulative air exposure time. From oven drying of the sample, the amount of moveable water is 2.4 grams. By dividing the actual water loss (the decrease in sample weight) to the total moveable water, the actual water loss in percent is calculated, which then plots on the secondary Y axis in Figure 5.24.

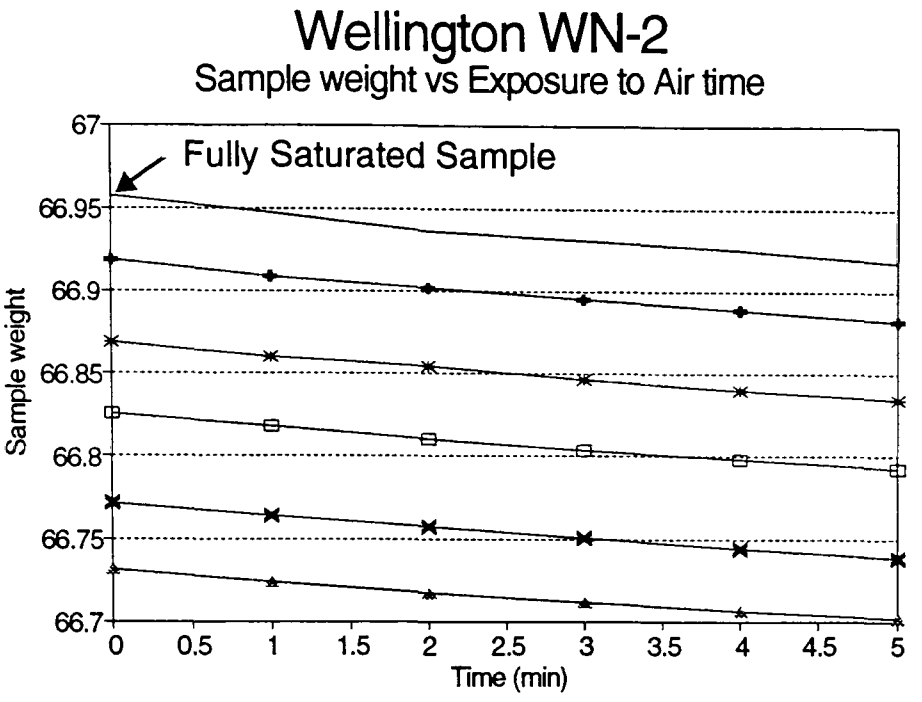


Figure 5.23 Changes in Weight as a Function of Air Exposure Time

Figure 5.24 shows that the rate of water loss as a function of air exposure time is more or less constant, up to about 22% loss of water in place where the experiment was stopped after a thin crack on the sample surface was observed.

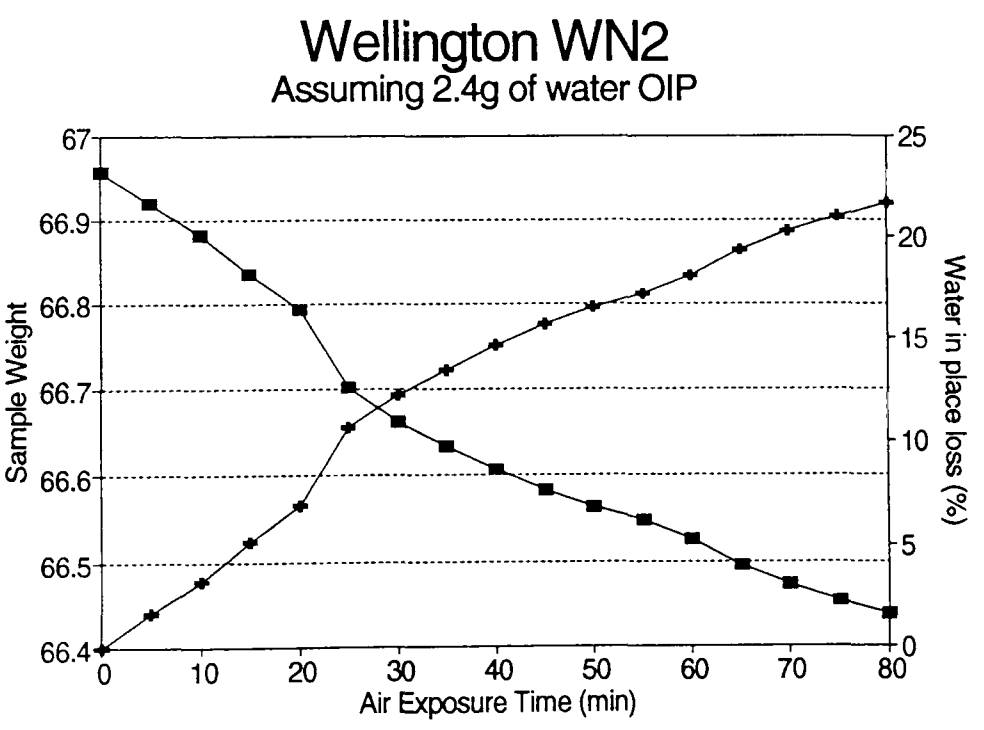


Figure 5.24 Sample Weight and Loss of Water in Place as a Function of Cumulative Exposure Time

Figure 5.25 shows a typical error bar plot of the electromagnetic measurement of a shale. As error-bar can not be plot in the customary log-log plot for conductivity, Figure 5.26 shows the variance plot which shows the span of the variance (the data plus and minus the error-bar) with the actual data removed. The plot shows that the error bar is very small along the frequency of interest. The largest error bar, at the lower end of the high frequency measurement range, is less than 7%. This largest error bar is at around 20 MHz where the data are a bit noisier.

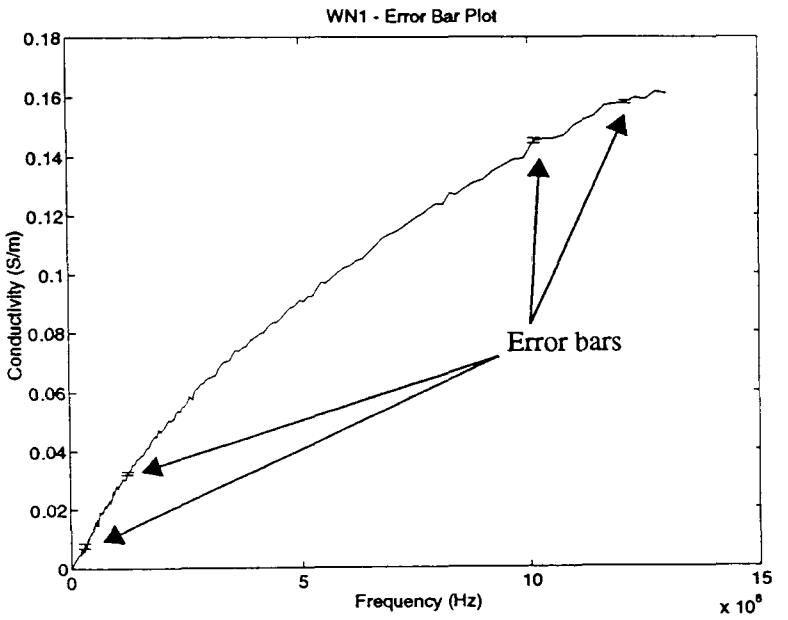


Figure 5.25 Error Bar Plot of a Shale Measurement

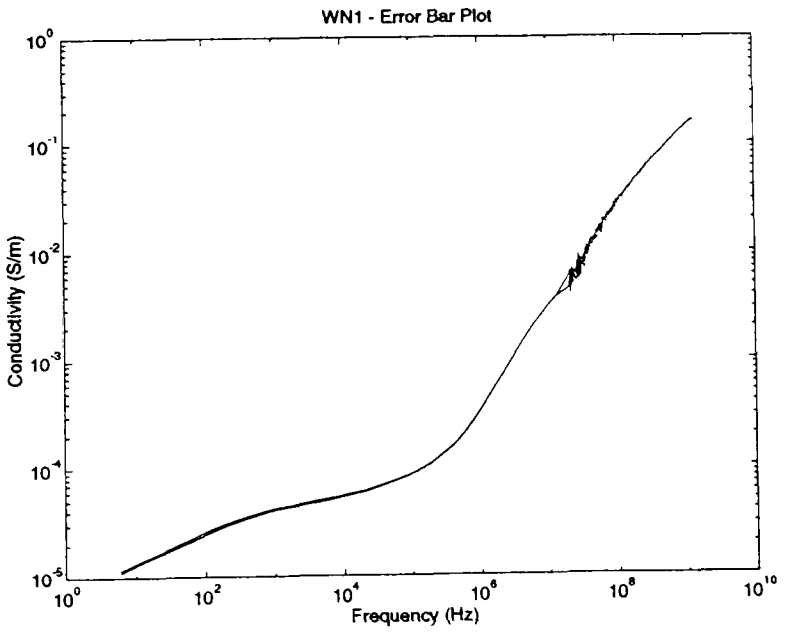


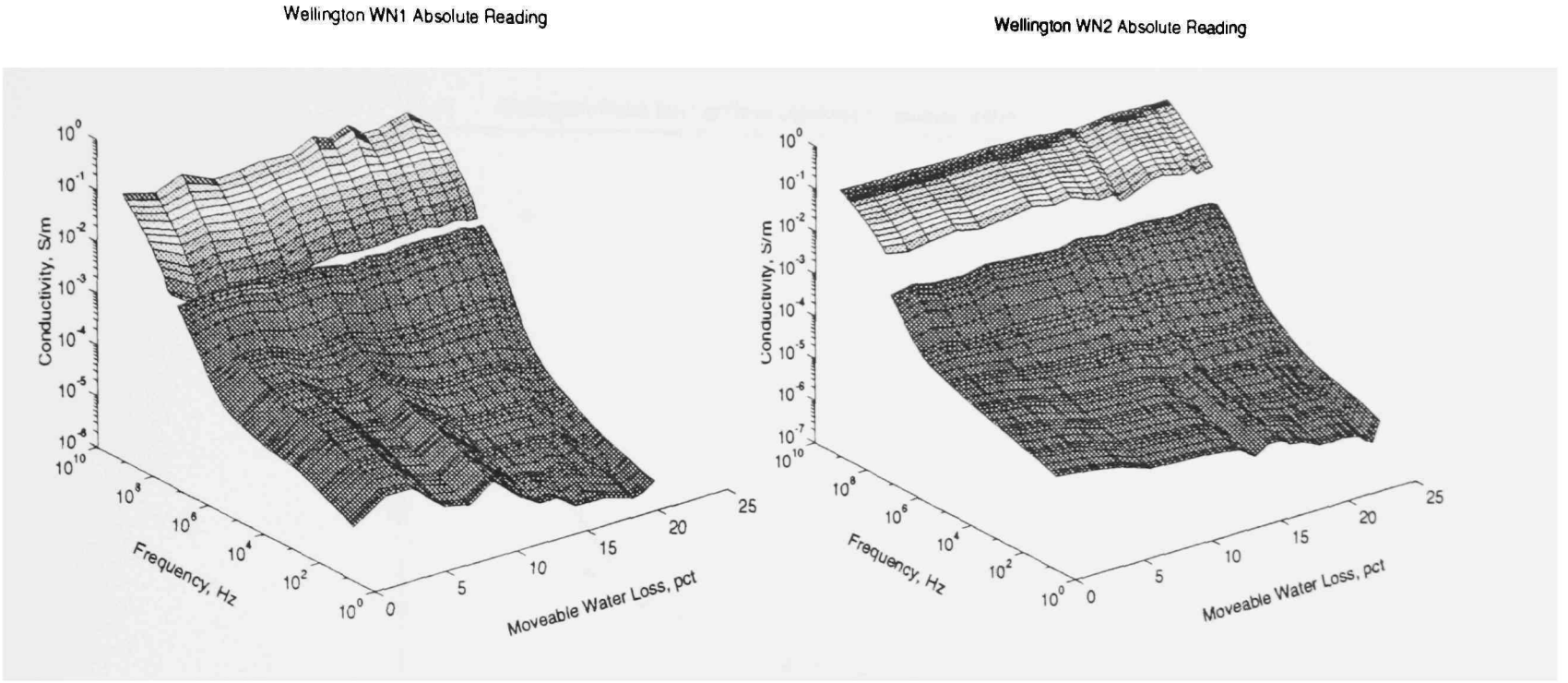
Figure 5.26 Variance Range of a Shale Measurement

The following figures show the result of electromagnetic measurements on 4 (four) Wellington shale samples. The electromagnetic parameters (conductivity, dielectric constant, and dissipation factor) are plotted on the z-axis, as a function of frequency and the amount of water loss in percent.

Figure 5.27 shows the conductivity of four Wellington shale samples WN1, WN2, WN4, and WN5 as a function of frequency and water loss. Sample WN3 was not included in the research as that sample cracked during preparation time. All plots show a trend of declining conductivity as frequency decreases and also as the amount of water loss increases. Figures 5.27a and 5.27c show that the two measurement methods more or less create a continuous trend. Figures 5.27b and 5.27d, however, show a distinct gap in the frequency. One explanation for the gap is due to heterogeneity of the sample; as different measurement techniques read different areas, slight changes in properties will be recognized more on one method than the other. The low frequency setup that uses the parallel-plate method will read the whole sample surface and across the sample thickness, basically averaging the property of the medium. The high frequency setup uses an open-ended probe that has a diameter of less than half of the sample diameter; thus this probe only reads whatever is right on the center of the sample surface. Hence a high spot on the center of the sample will easily skew the high frequency measurements.

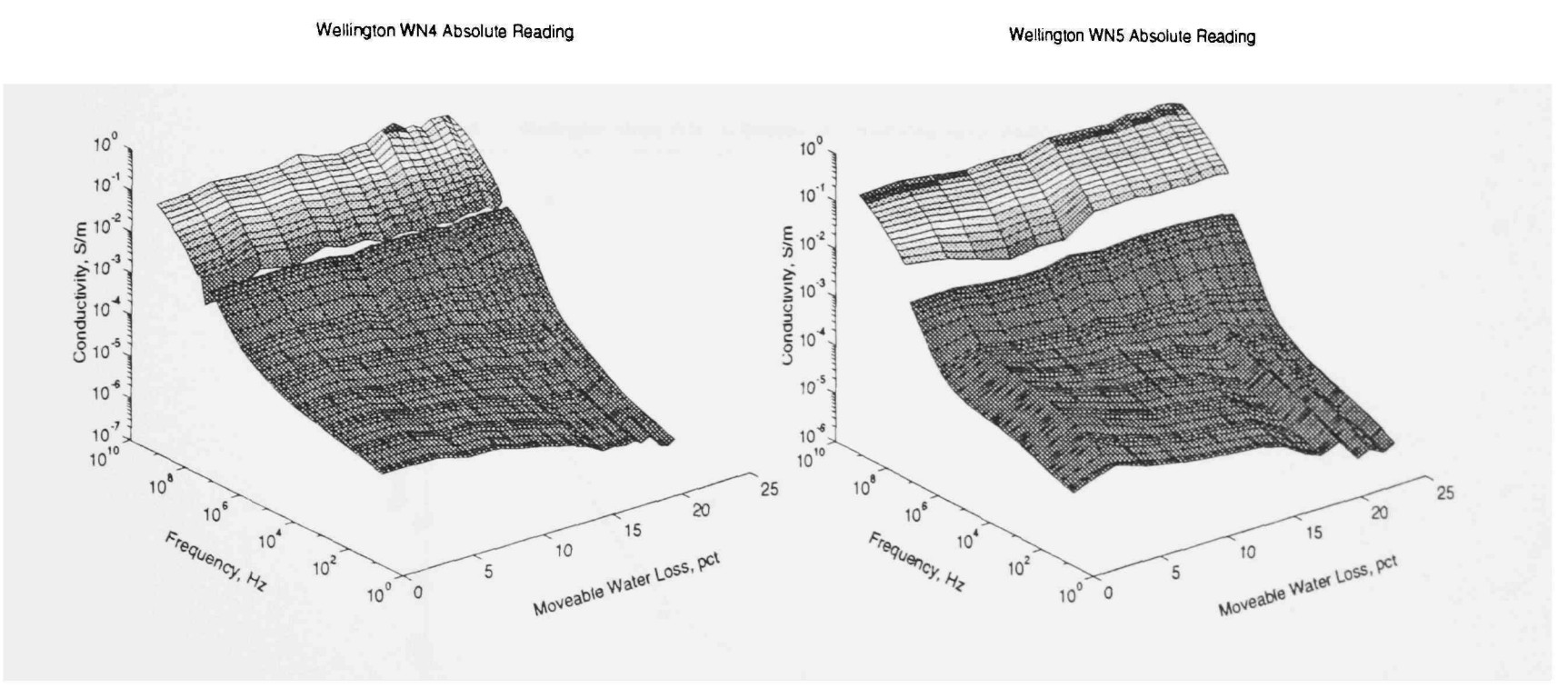
To better look at the changes of conductivity as water content decreases at logging tool frequencies, one can do a cross-section cut on Figure 5.27 parallel to the water loss axis at the specific tool frequency. Figures 5.28 through 5.33 shows conductivity of sample Wellington WN1 at 35 Hz (Deep Laterolog tool), 280 Hz (Shallow Laterolog tool), 20 kHz (induction type tool), 10 MHz, 250 MHz (MWD tool), and 1.1 GHz (dielectric tool). Ignoring the first data point that has a lower conductivity than the others, the conductivity drops rapidly in the first 5% water loss and then levels off, as seen at 35 Hz, 280 Hz, and 20 kHz in Figure 5.28, 5.29, and 5.30, respectively. This drop in conductivity is less defined at 10 Mhz and vanishes at 250 MHz and 1.1 GHz.

Figure 5.34 shows the dielectric constant as a function of frequency and water loss in percent, and Figures 5.35 up to 5.40 show the dielectric constant at various logging tool frequencies as a function of water loss.



(a) Wellington WN1

(b) Wellington WN2



(c) Wellington WN4

(d) Wellington WN5

Figure 5.27 Conductivity of Wellington Shales as a Function of Frequency and Water Loss.

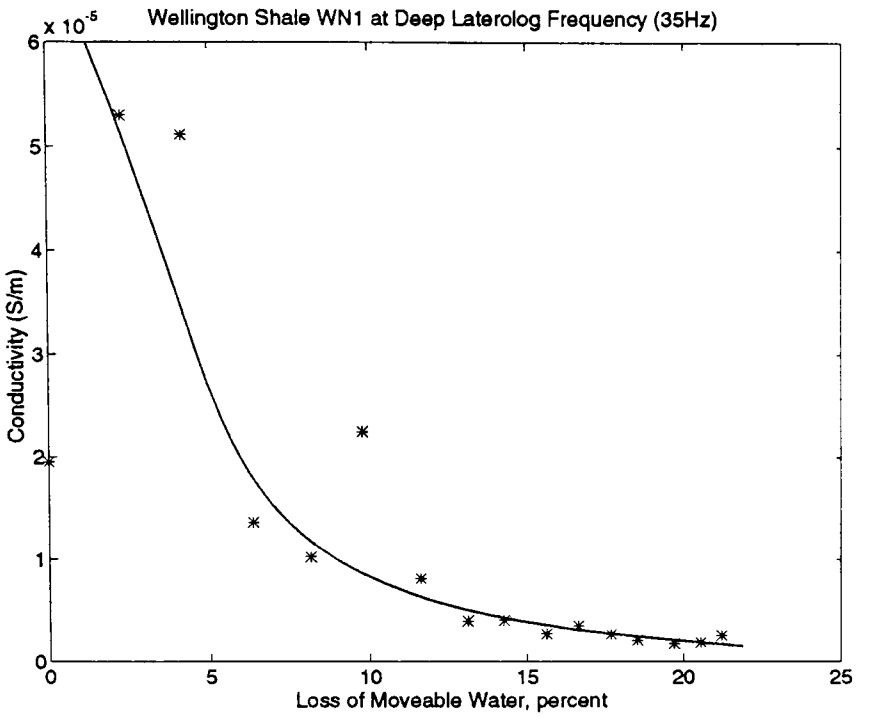


Figure 5.28 Conductivity of Wellington WN1 at 35 Hz as a Function of Water Loss

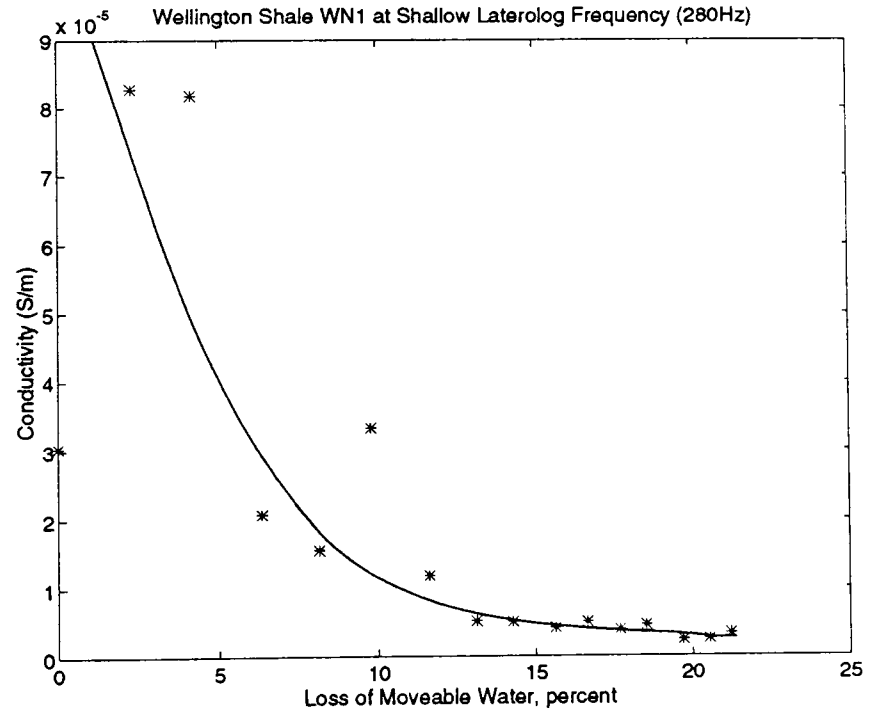


Figure 5.29 Conductivity of Wellington WN1 at 280 Hz as a Function of Water Loss

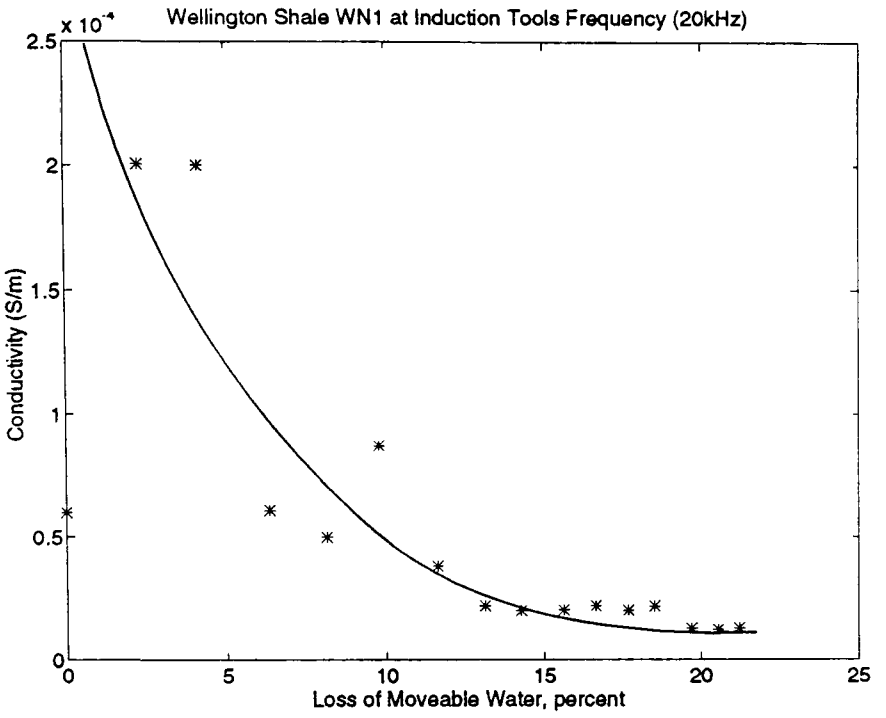


Figure 5.30 Conductivity of Wellington WN1 at 20 kHz as a Function of Water Loss

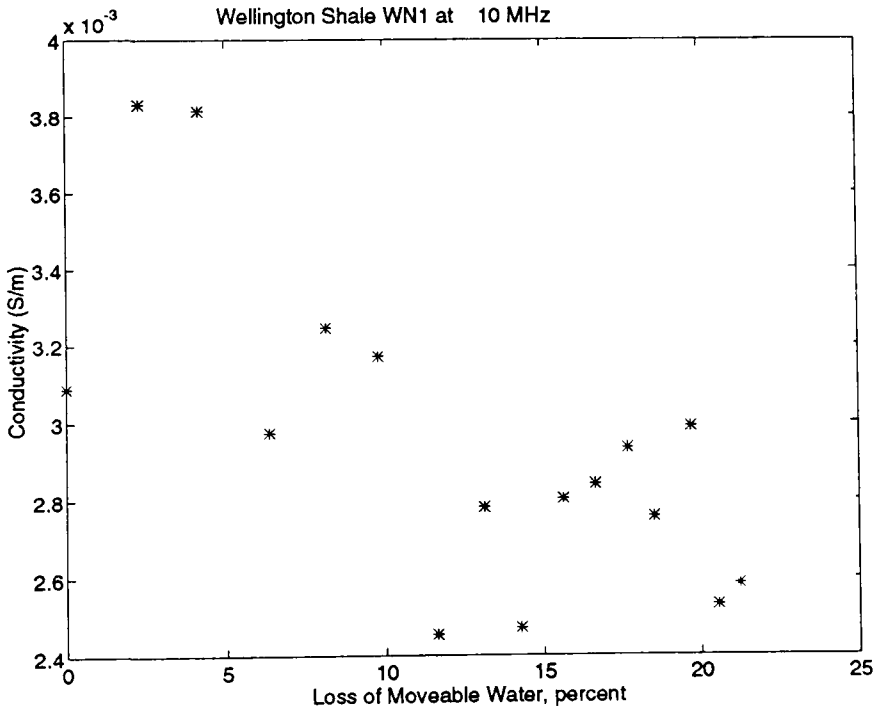


Figure 5.31 Conductivity of Wellington WN1 at 10 MHz as a Function of Water Loss

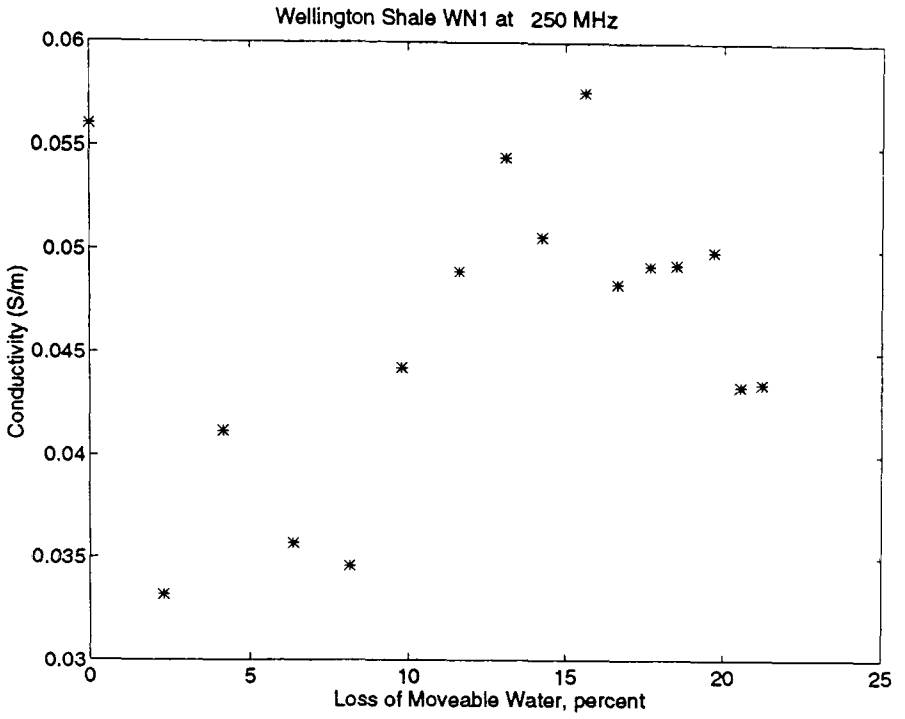


Figure 5.32 Conductivity of Wellington WN1 at 250 MHz as a Function of Water Loss

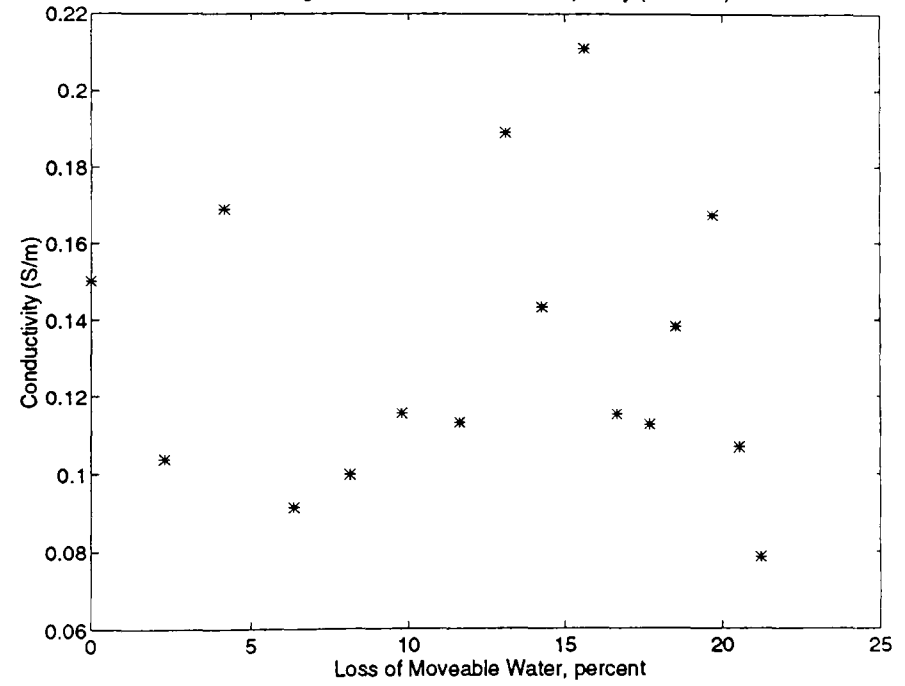


Figure 5.33 Conductivity of Wellington WN1 at 1.1 GHz as a Function of Water Loss

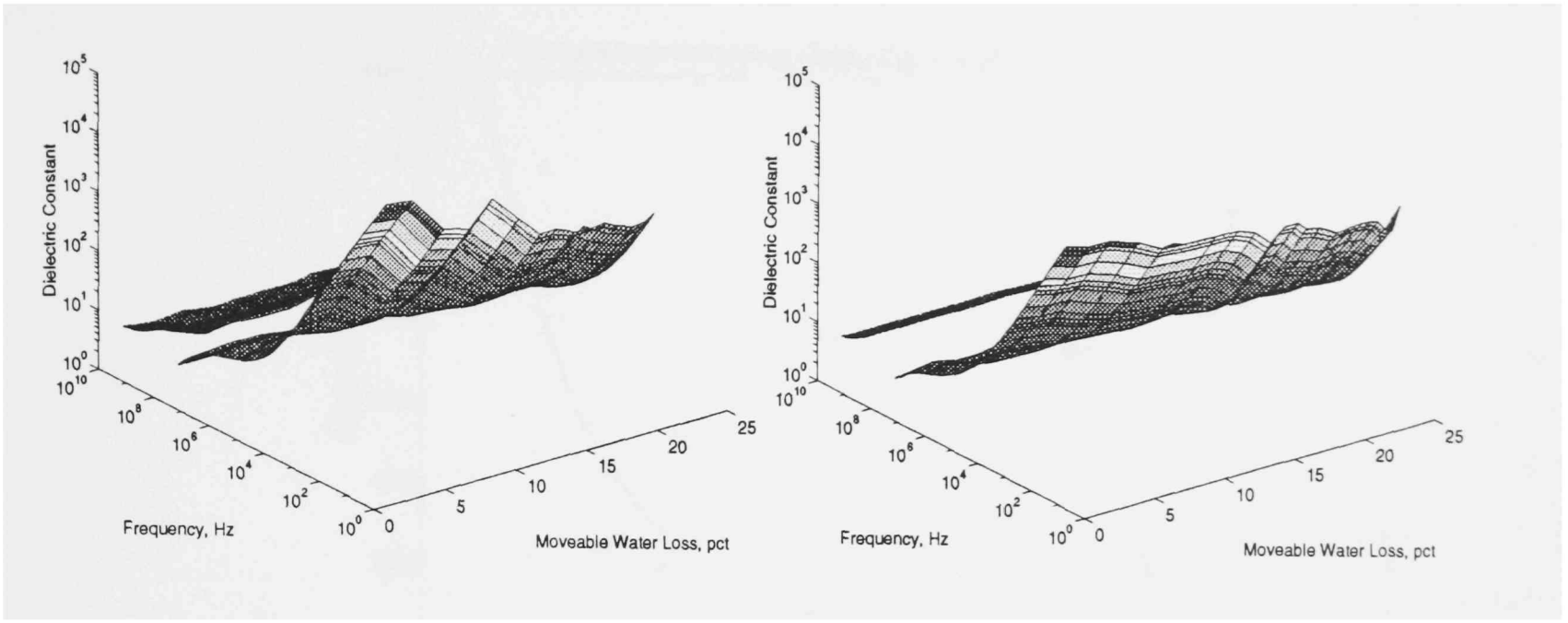
Figure 5.34 shows that the dielectric constant of Wellington shales is not "constant" along the frequency axis, decreasing in magnitude as the frequency increases. Also the jump of the dielectric constant at the measurement gap can be seen on the plots. Currently there is no explanation for this occurrence of the gap. At logging tool frequencies of 35 Hz and 280 Hz, shown in Figures 5.35 and 5.36, the dielectric constant of Wellington WN1 shale drops rapidly in the first 10% of water loss as the sample dries out. This trend changes into a more-or-less linear fashion at 20 kHz and 10 MHz, as shown in Figures 5.37 and 5.38, respectively. At higher frequencies, 250 MHz and 1.1 GHz, no pattern was observed, as shown in Figures 5.39 and 5.40, respectively.

Figure 5.41 shows the dissipation factor of Wellington shales as a function of frequency and water loss. Similar to the dielectric constant plots, there is a gap in the dissipation factor at the frequency gap that the author is unable to explain. Also the distinct peak (local maxima) is clearly seen on the plots, and the magnitude of the peak decreases as the sample gets drier. Also a local minima can be seen on the figure, but the details are obstructed behind the "mountain." Figures 5.42 up to 5.45 plot the characteristics of the local maxima and minima of Wellington shales as a function of water loss, so the maxima and minima can be better analyzed. Those figures show that both local maxima and local minima drop both in frequency and magnitude as the sample gets drier. This characteristic is consistent on all of the four samples. The outcome is very interesting because either by using those characteristics individually or in combination, sample's water content can be determined. One example of application is on well logging. By comparing the dissipation factor characteristic from different logs on the same formation type, the formation water saturation can be qualitatively approximated. Another potential application is on time lapsed MWD situation where the dissipation factor characteristics can be displayed at the drill floor real time and can be used to predict the onset of wellbore instability. There are several technical obstacles for applying these methods: the tool must operate at a much lower frequency than that of the current MWD tools, and also be of variable frequency instead of the single frequency mode of the current tools.

Figures 5.46 to 5.51 show the dissipation factor of sample Wellington WN1 as a function of water loss at several frequencies. At 35 Hz, the dissipation factor shows no pattern as the sample dries out. At 280 Hz the plot shows that the dissipation factor peaks whenever the sample loses 6% of its water content, and then drops down as the sample further dries out. At 20 kHz, the dissipation factor shows an asymptotic decrease, and no pattern was shown for frequencies higher than 10 MHz.

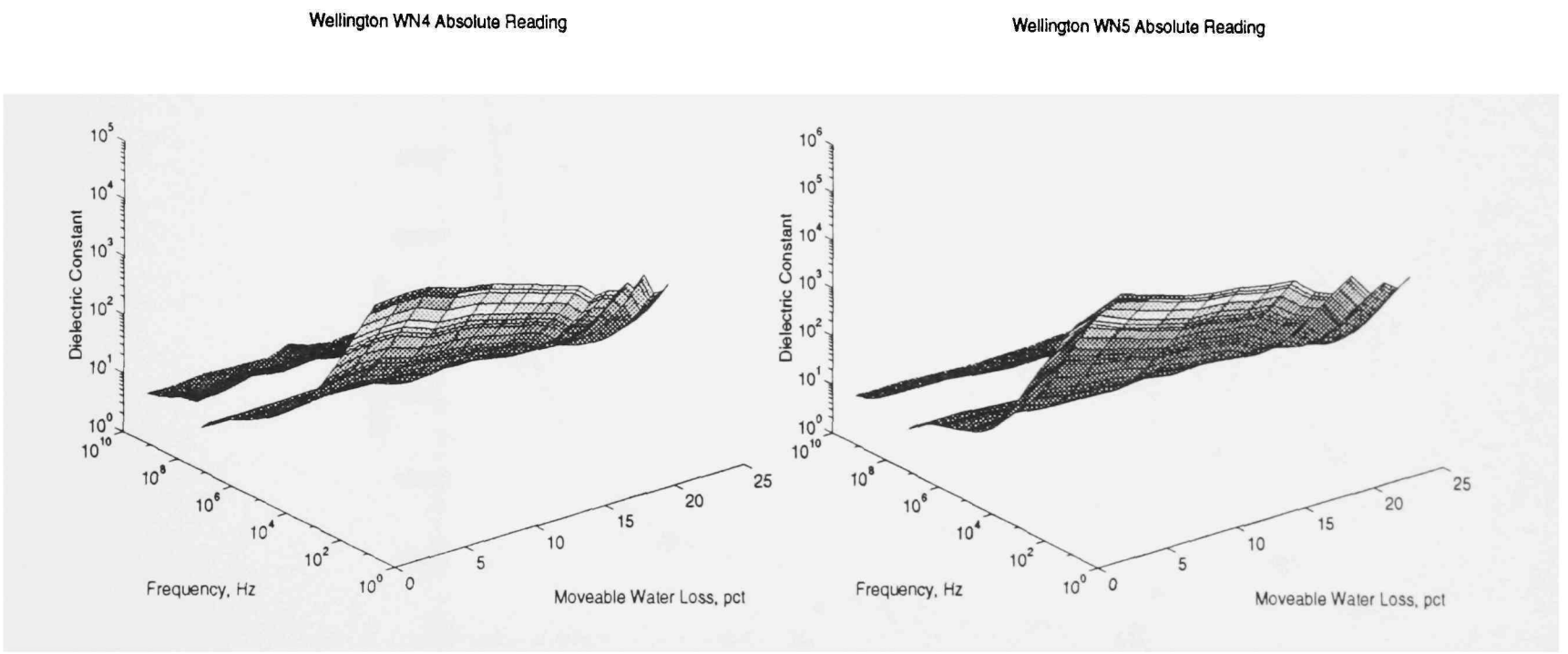
Appendix A contains more plots of the other Wellington shale samples at logging frequencies, similar to that already shown in this section.

The conclusions of the air evaporation experiment are as follows: (1) conductivity and dielectric constant drop with increasing water loss; (2) changes in conductivity and dielectric constant are more detectable at lower frequencies; (3) the location and magnitude of both the local maxima and minima of the dissipation factor can be used as indicators of shale water content; (4) by comparing the dissipation factor characteristic from different well-logs on the same formation type, the formation water saturation can be qualitatively approximated; (5) dissipation factor characteristics from MWD tools can be displayed at the drill floor real time and can be used to predict the onset of wellbore instability; and (6) well logging tools and MWD tools need to be modified to work at a much lower frequency and to be of variable frequency.



(a) Wellington WN1

(b) Wellington WN2



(c) Wellington WN4

(d) Wellington WN5

Figure 5.34 Dielectric Constant of Wellington Shale as a Function of Frequency and Water Loss.

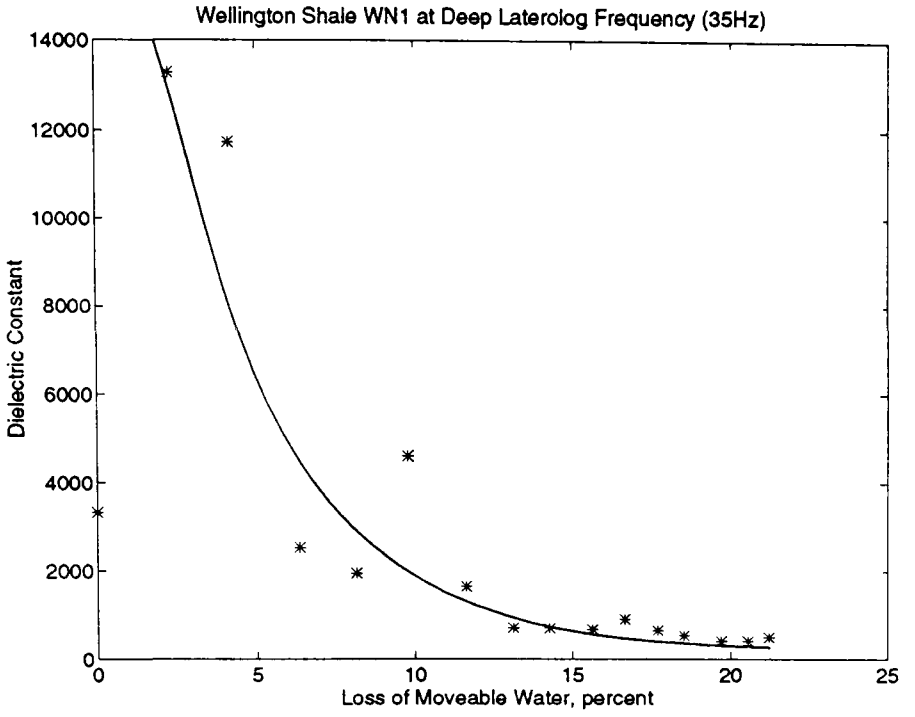


Figure 5.35 Dielectric Constant of Wellington WN1 at 35 Hz as a Function of Water Loss

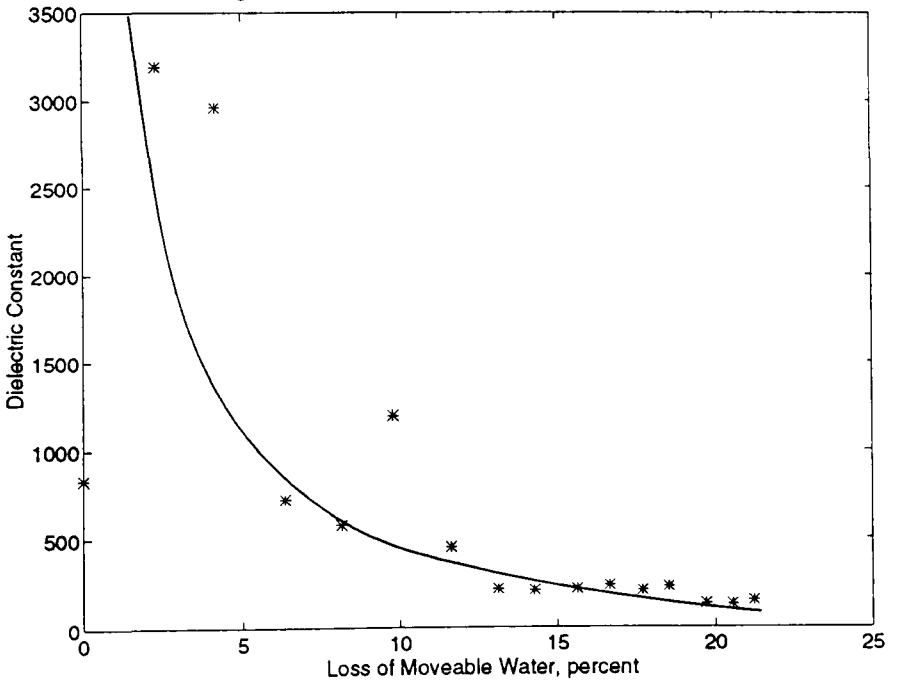


Figure 5.36 Dielectric Constant of Wellington WN1 at 280 Hz as a Function of Water Loss

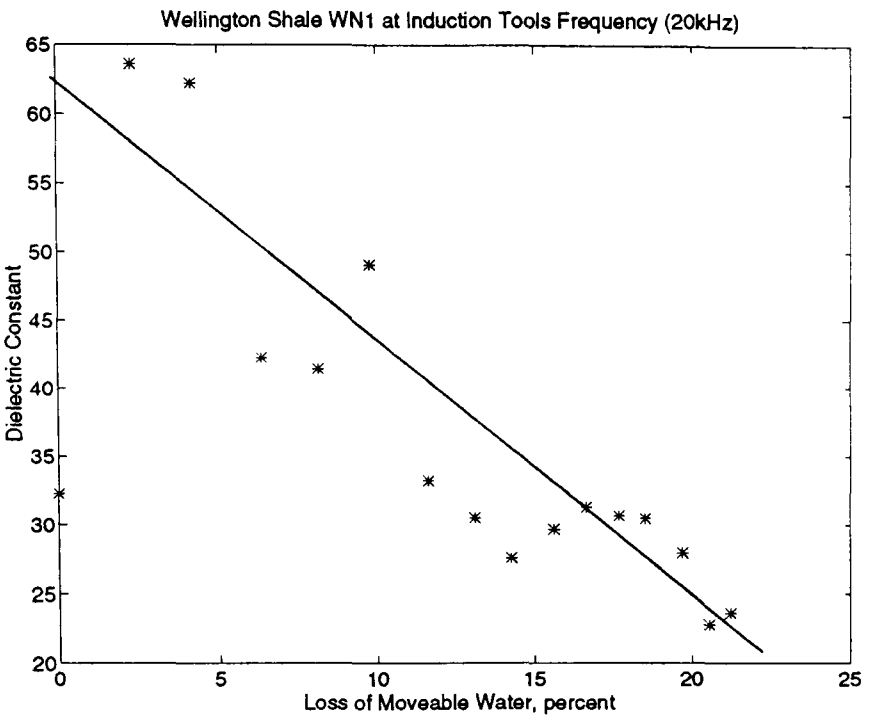


Figure 5.37 Dielectric Constant of Wellington WN1 at 20 kHz as a Function of Water Loss

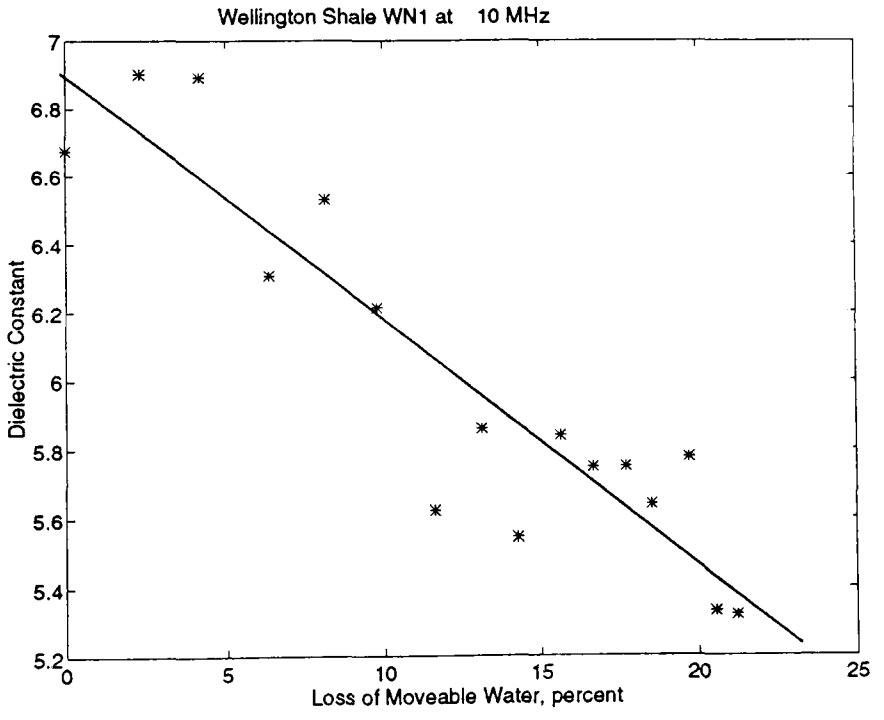


Figure 5.38 Dielectric Constant of Wellington WN1 at 10 MHz as a Function of Water Loss

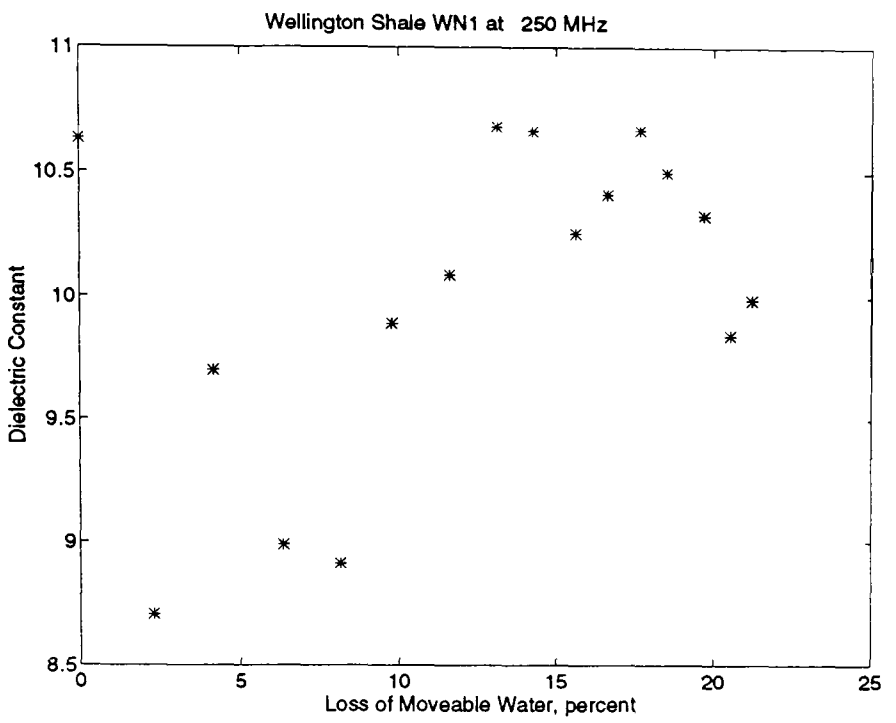


Figure 5.39 Dielectric Constant of Wellington WN1 at 250 MHz as a Function of Water Loss

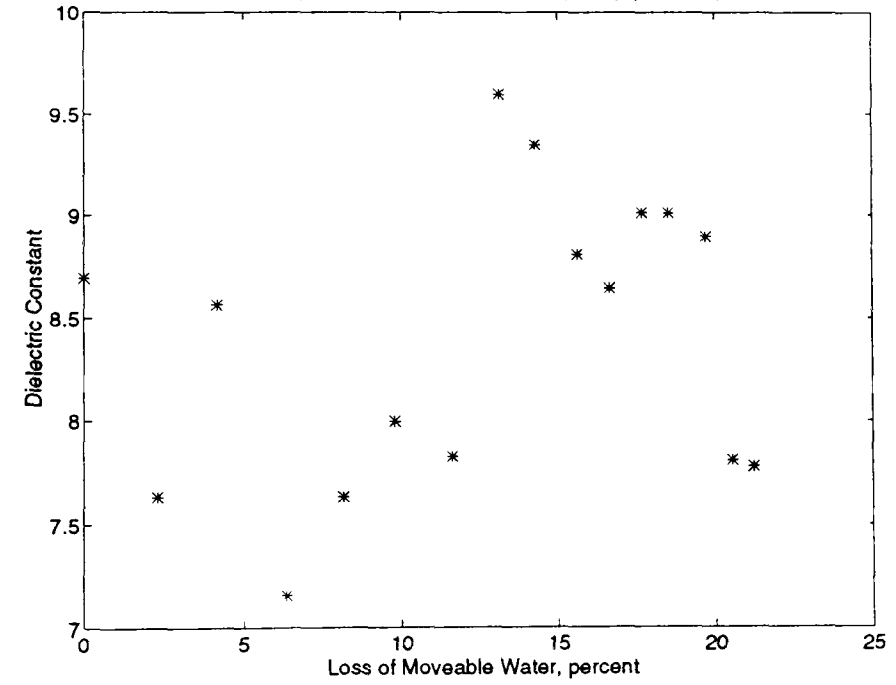
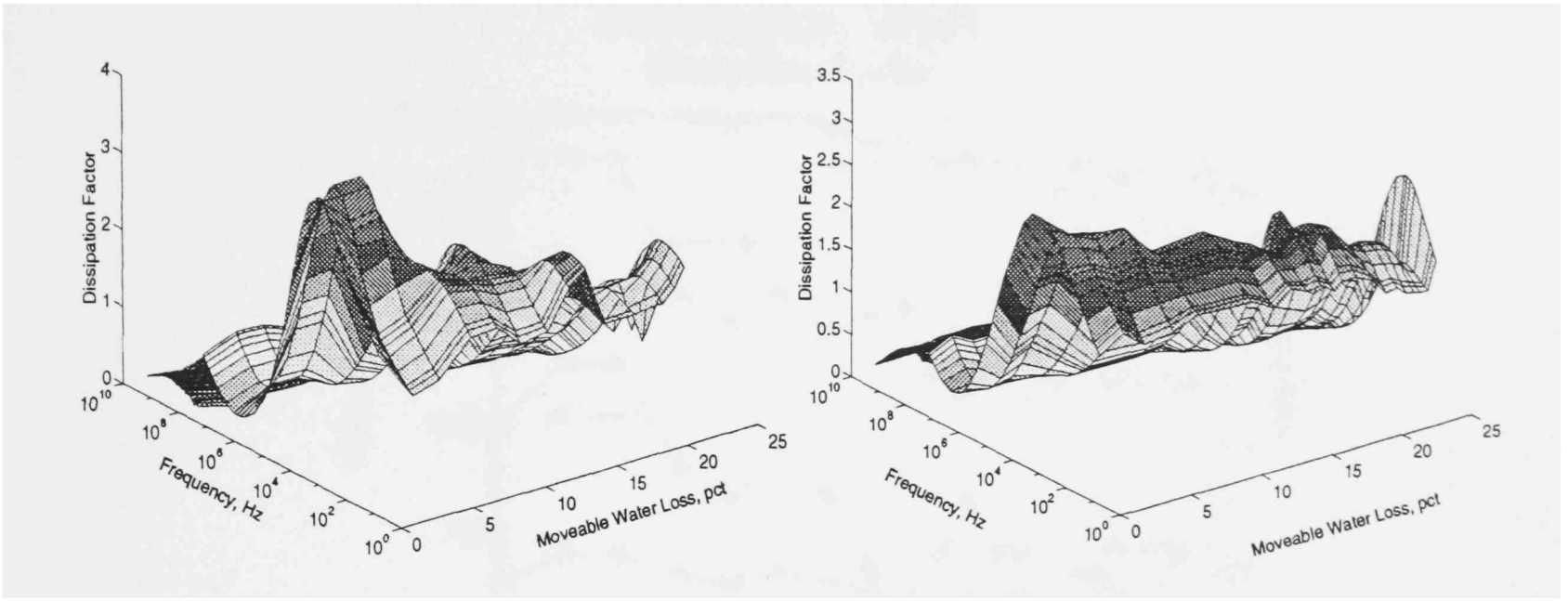
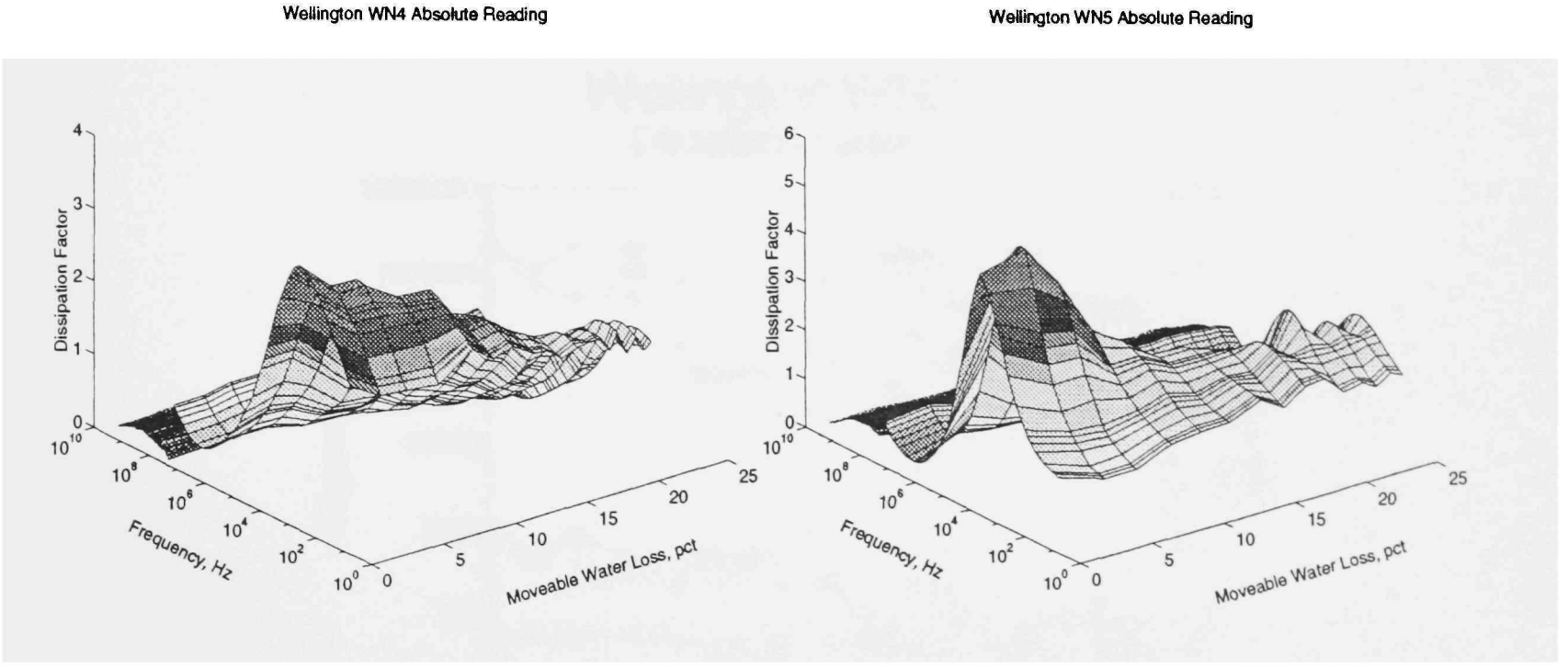


Figure 5.40 Dielectric Constant of Wellington WN1 at 1.1 GHz as a Function of Water Loss



(a) Wellington WN1

(b) Wellington WN2



(c) Wellington WN4

(d) Wellington WN5

Figure 5.41 Dissipation Factor of Wellington as a Function of Frequency and Water Loss.

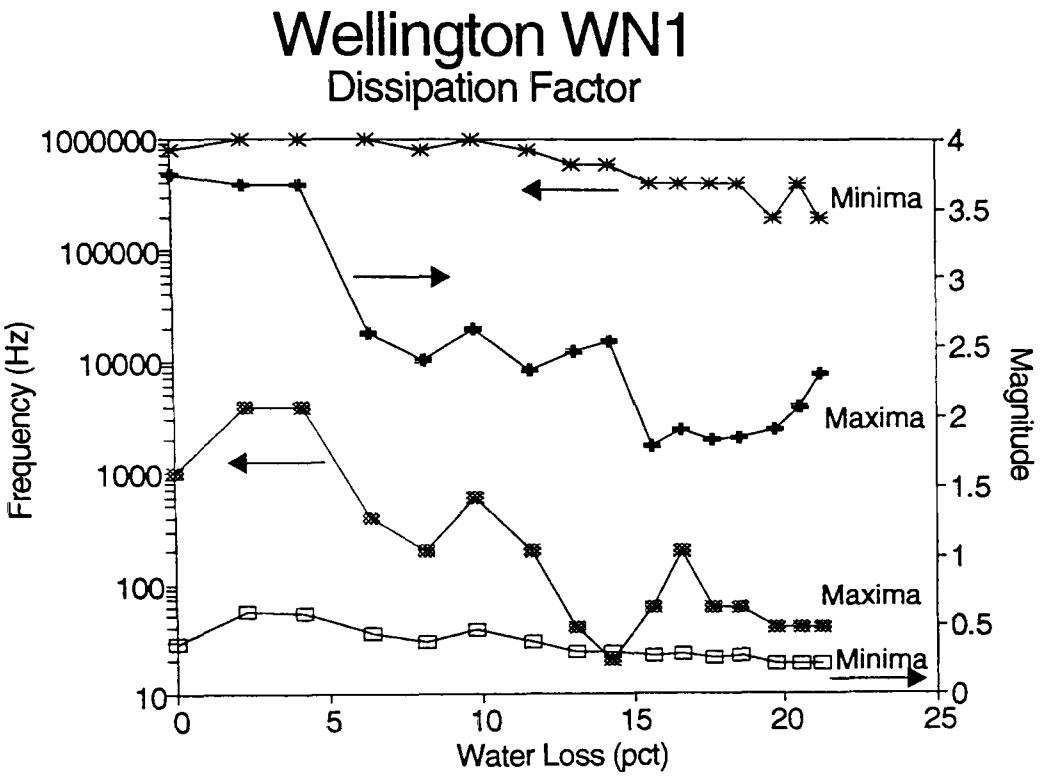


Figure 5.42 Local Maxima and Minima of the Dissipation Factor of Wellington WN1 as a Function of Water Loss

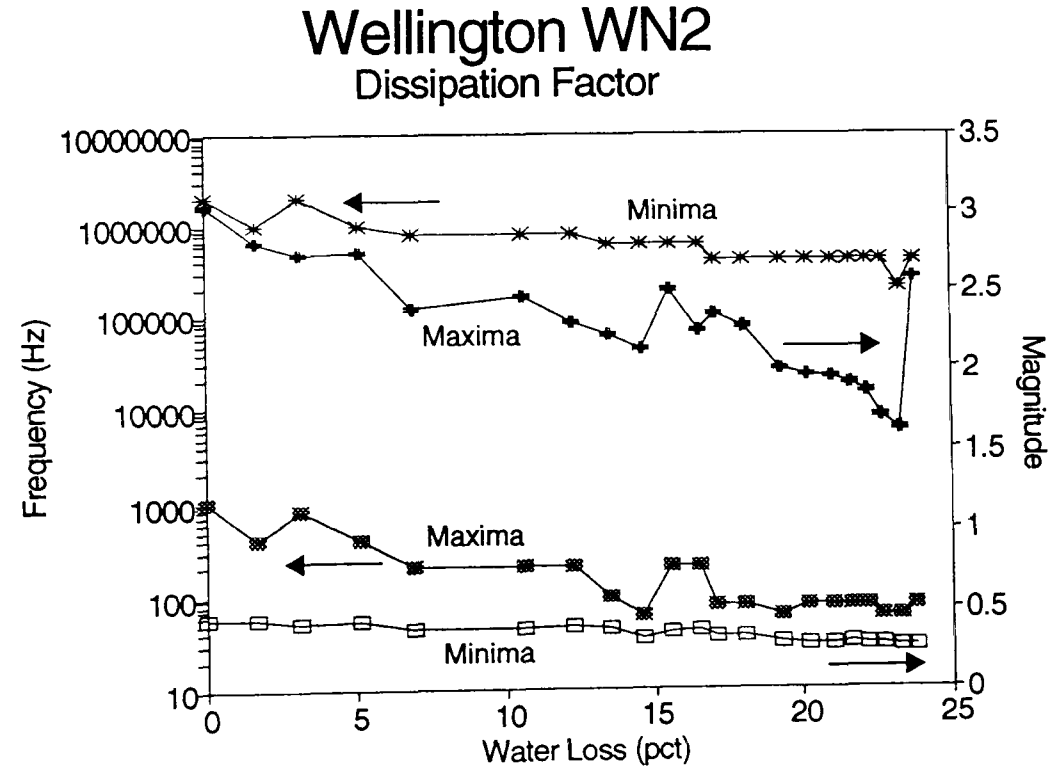


Figure 5.43 Local Maxima and Minima of the Dissipation Factor of Wellington WN2 as a Function of Water Loss

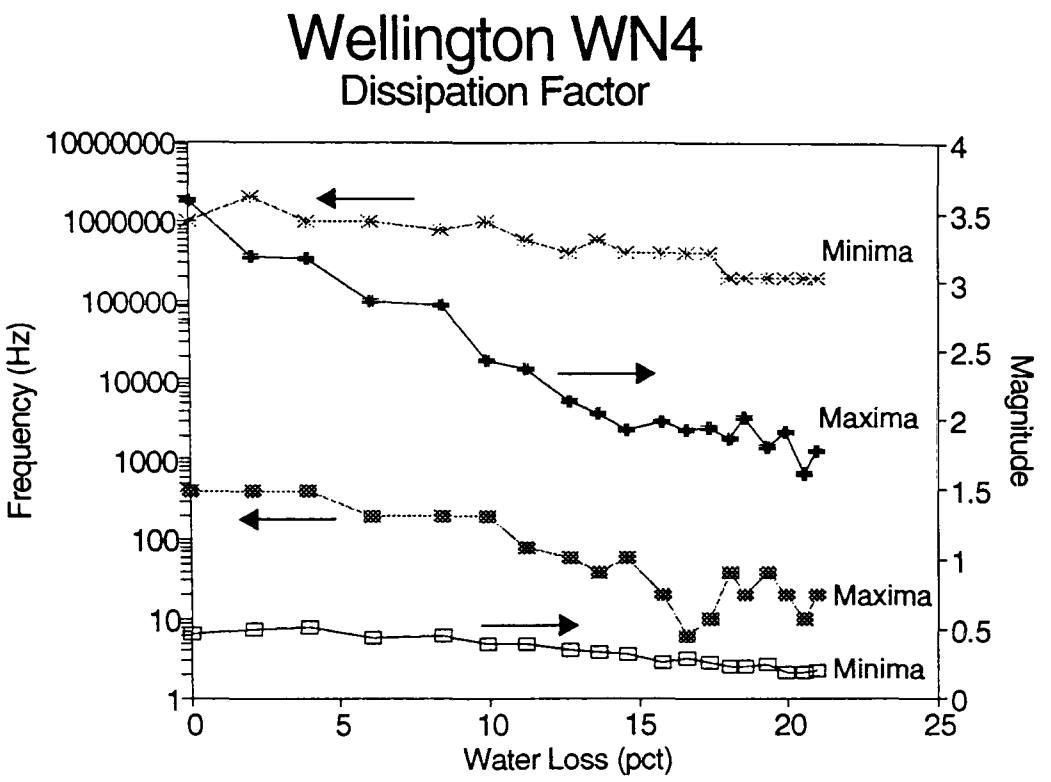


Figure 5.44 Local Maxima and Minima of the Dissipation Factor of Wellington WN4 as a Function of Water Loss

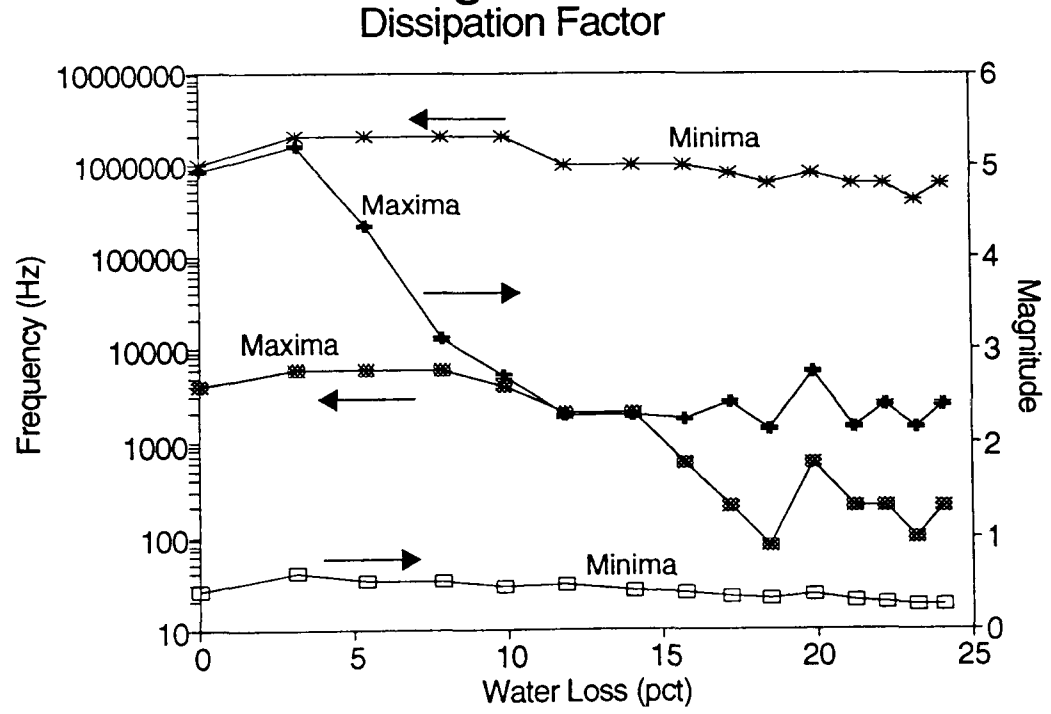


Figure 5.45 Local Maxima and Minima of the Dissipation Factor of Wellington WN5 as a Function of Water Loss

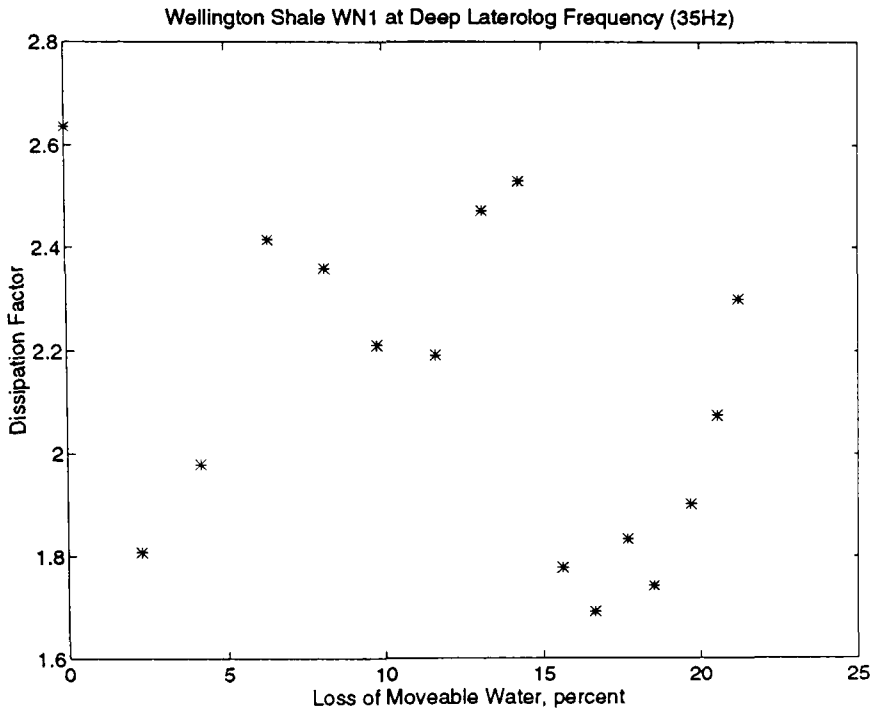


Figure 5.46 Dissipation Factor of Wellington WN1 at 35 Hz as a Function of Water Loss

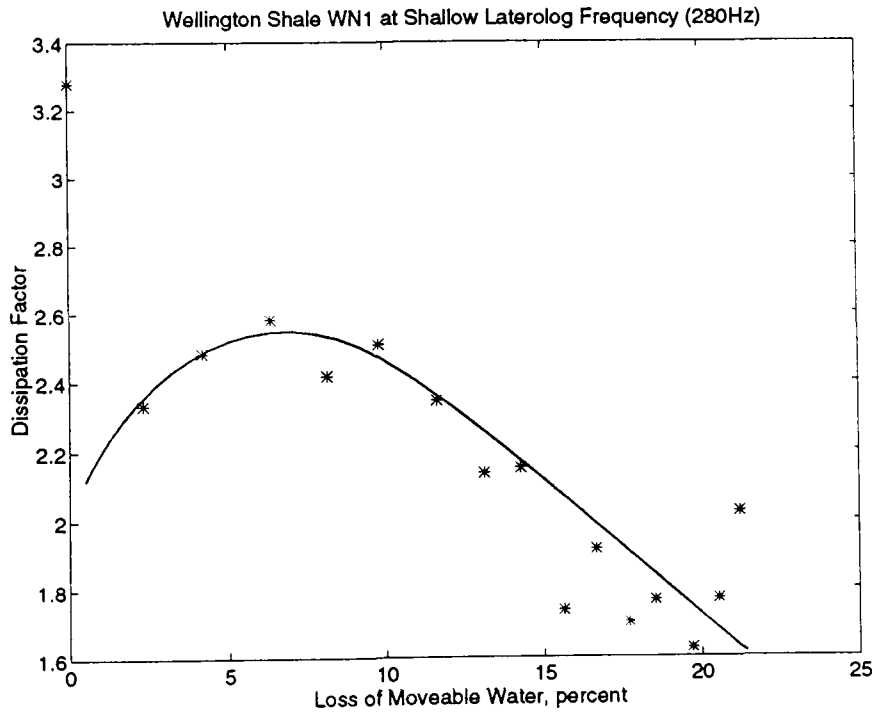


Figure 5.47 Dissipation Factor of Wellington WN1 at 280 Hz as a Function of Water Loss

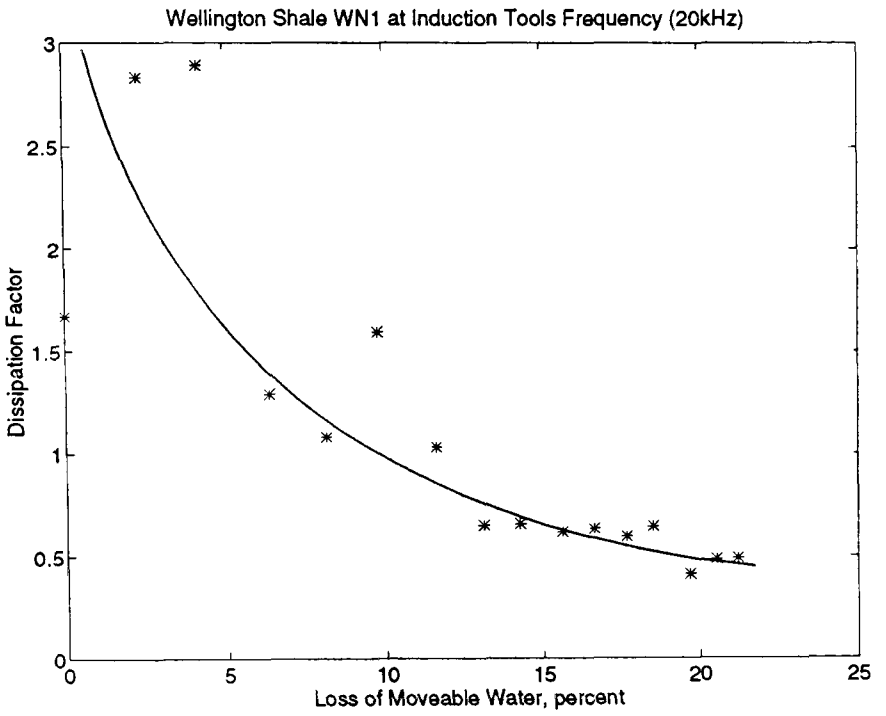


Figure 5.48 Dissipation Factor of Wellington WN1 at 20 kHz as a Function of Water Loss

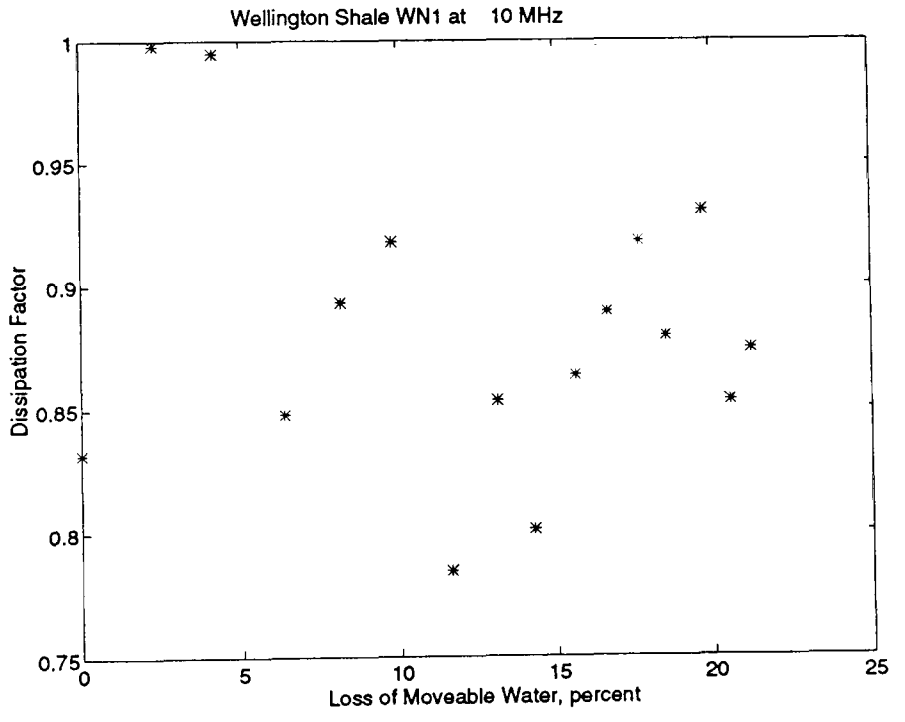


Figure 5.49 Dissipation Factor of Wellington WN1 at 10 MHz as a Function of Water Loss

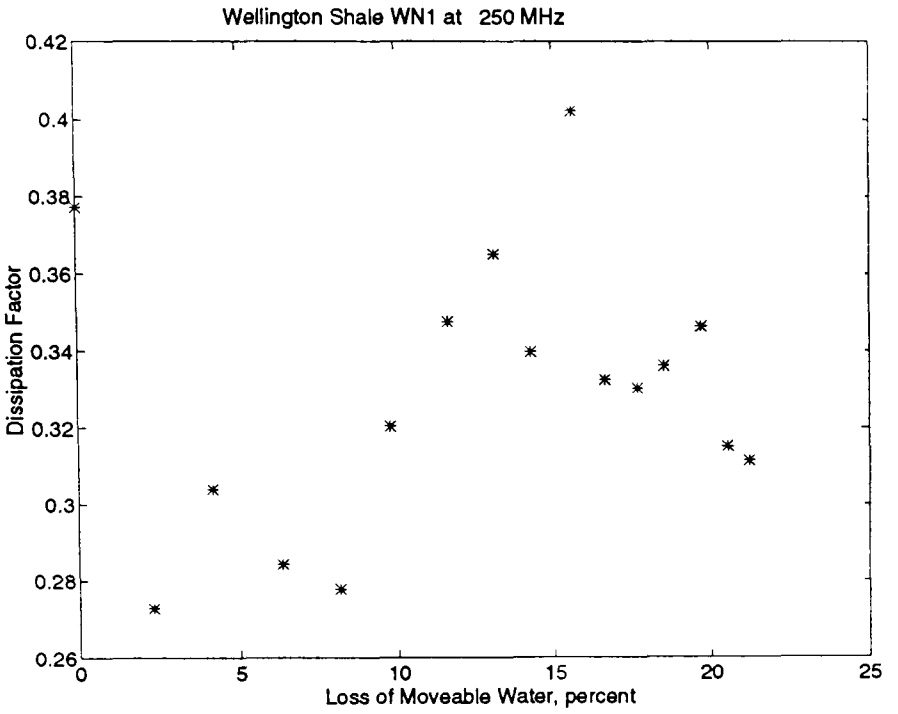


Figure 5.50 Dissipation Factor of Wellington WN1 at 250 MHz as a Function of Water Loss

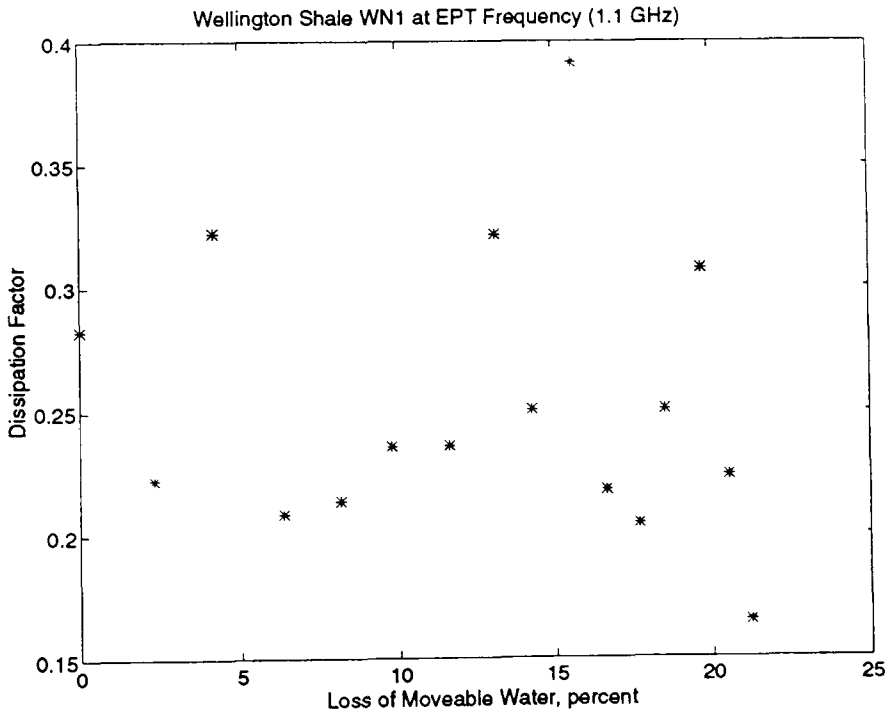


Figure 5.51 Dissipation Factor of Wellington WN1 at 1.1 GHz as a Function of Water Loss

CHAPTER VI

INDUCED POTENTIAL ON SHALE

This chapter will describe the Induced DC potential that has been observed on various shale samples.

6.1 Induced DC Phenomena

The induced DC phenomenon was first observed on the low-frequency measurement setup. To ensure a good consistent contact between the sample surface and the measurement probe, a weight had to be used. The weight that was impressed on the shale appears to have caused ionic movement, creating an electrical current. This electrical current in turn piled at the sample-to-electrode contact as the ions could not move into the solid electrode. This ionic build-up appeared as a resistance known as *contact resistance* that increased with time. This increase of the contact-resistance with time was first thought to be due to a leak in the equipment, but after a thorough equipment check, it was concluded that this current was coming from the sample itself.

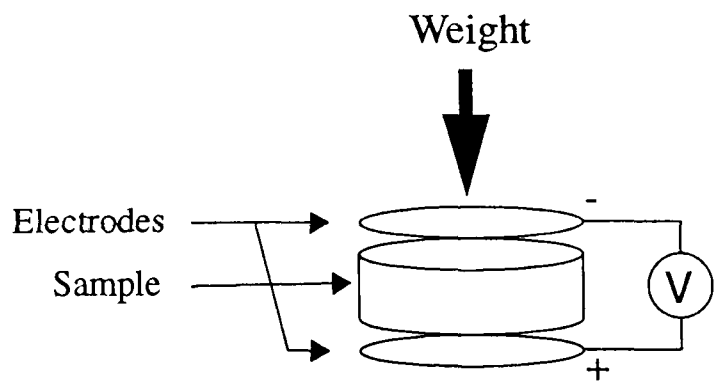


Figure 6.1 Schematic Diagram for Induced DC Measurement

Figure 6.1 shows the measurement setup and the polarity that happened on all measurements, the top (weight side) is more negative with respect to the other (base) side.

Figure 6.2 shows the magnitude of the Induced DC voltage of a Wellington shale as a function of load on the sample. This experiment uses a sample that sits on a table and is loaded with a dead-weight method.

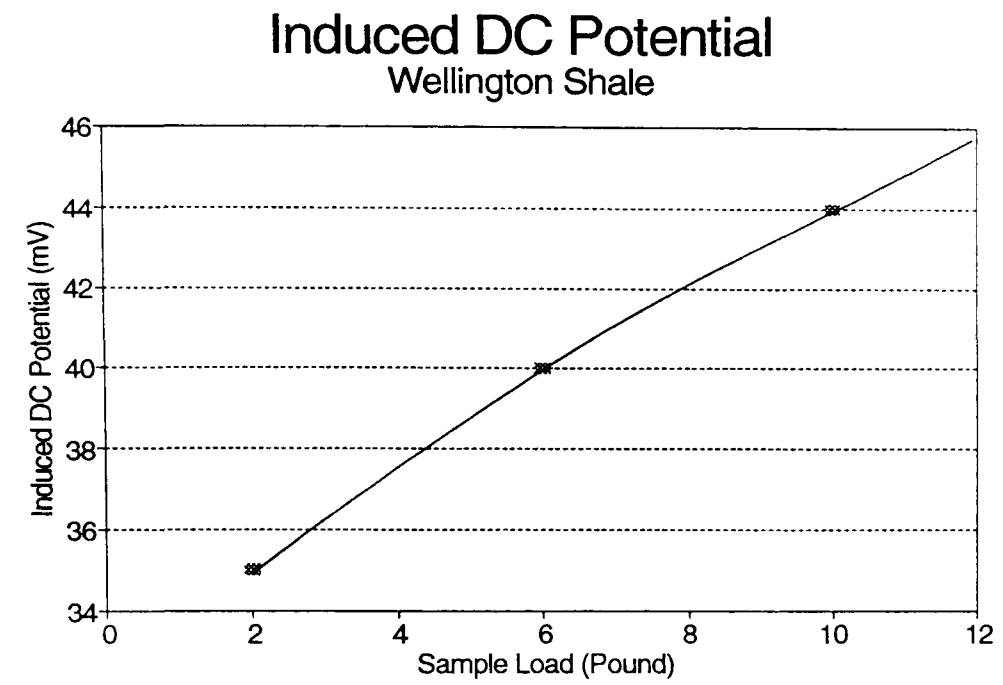


Figure 6.2 Induced DC versus Load

The magnitude of the Induced DC potential with time under 1 megaohm resistive load on the voltmeter is shown in Figure 6.3. This plot shows that the induced DC potential decreases logarithmically with time. The abrupt change that occurs at around 3000 seconds after the experiment started was due to an abrupt change of room temperature; when the room temperature controller switched into the "energy saving mode."

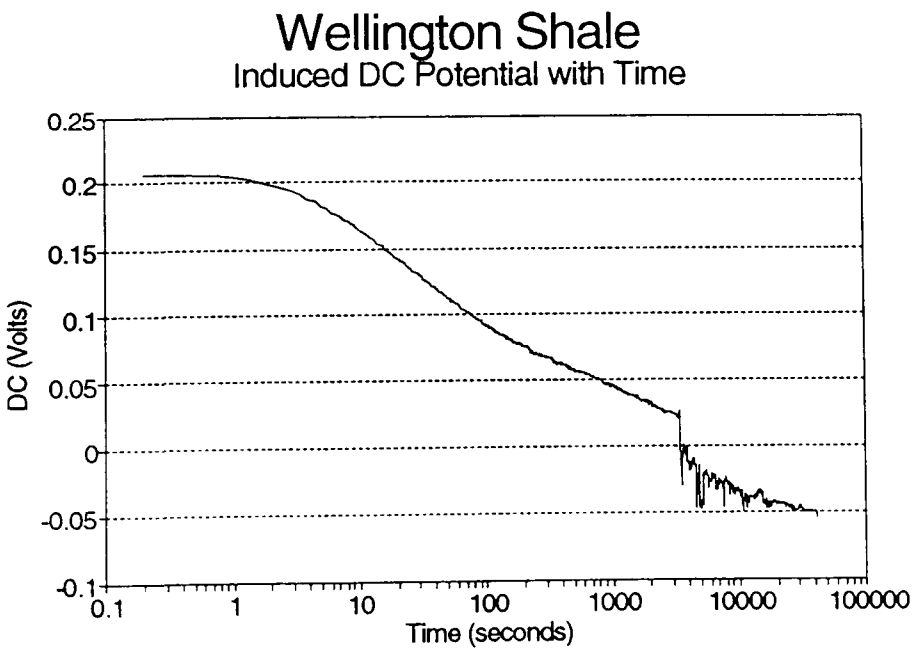


Figure 6.3 Induced DC with Time

In order to get more insight into the Induced DC potential phenomenon, several materials have been measured as shown in Figure 6.4. This plot shows the maximum voltage recorded of each sample that was loaded with 1000 pounds of constant load.

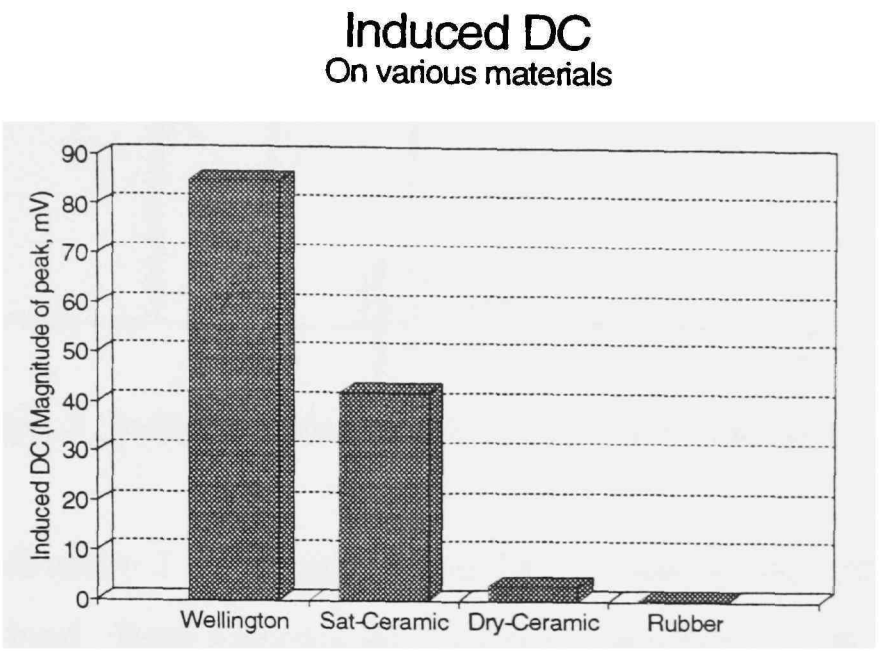


Figure 6.4 Induced DC on Various Materials

Figure 6.4 shows the comparison of induced DC from a Wellington shale, 1000 ppm NaCl brine saturated ceramic disc, dry ceramic disc, and a piece of rubber.

The plot shows that the induced DC is due to more than just a *piezo-electric* (the electric potential generated from grain-to-grain contact) effect. The piezo-electric magnitude is very low, around 3 mV, as shown on the response of the dry-ceramic sample. The induced DC from the effect of moving ions, around 42 mV, can be seen clearly from the saturated ceramic response. The higher response of Wellington shale can be attributed to higher pore water salinity and/or different type of anions/cations. The lack of response of the rubber sheet shows that the induced DC is not an equipment artifact.

This induced DC potential is not similar to the *induced polarization* phenomena as explained by several authors (Telford et al., 1990; Vinegar and Waxman, 1984) in which the rock sample acts like a "capacitor" that stays partially energized after the measurement current cut off. Figure 6.5 shows the transient decay in the rock sample where the rock sample was given a potential of V_c. And after the current was cut off, the potential across the

measurement electrode did not drop to zero instantaneously, but made a large decrease and then decayed slowly.

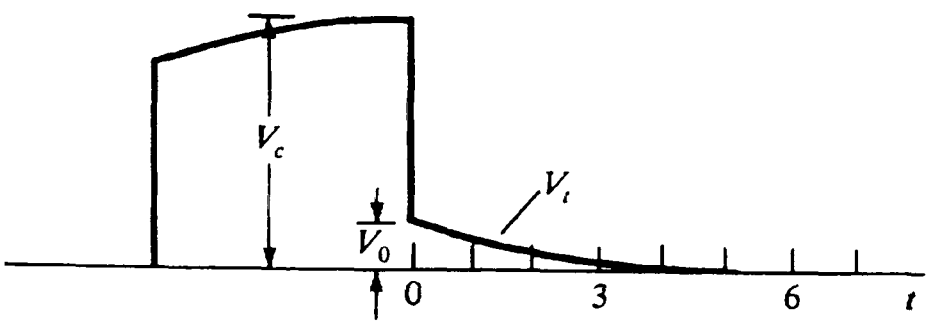


Figure 6.5 Induced Polarization Decay Curve (Telford et al., 1990)

Figures 6.6 and 6.7 show the induced DC on shale of two different sample lengths under a constant load. Both samples are 2 inches in diameter Wellington shales at native condition; the small one is 1/4 inch thick and the large sample is 2 inches thick.

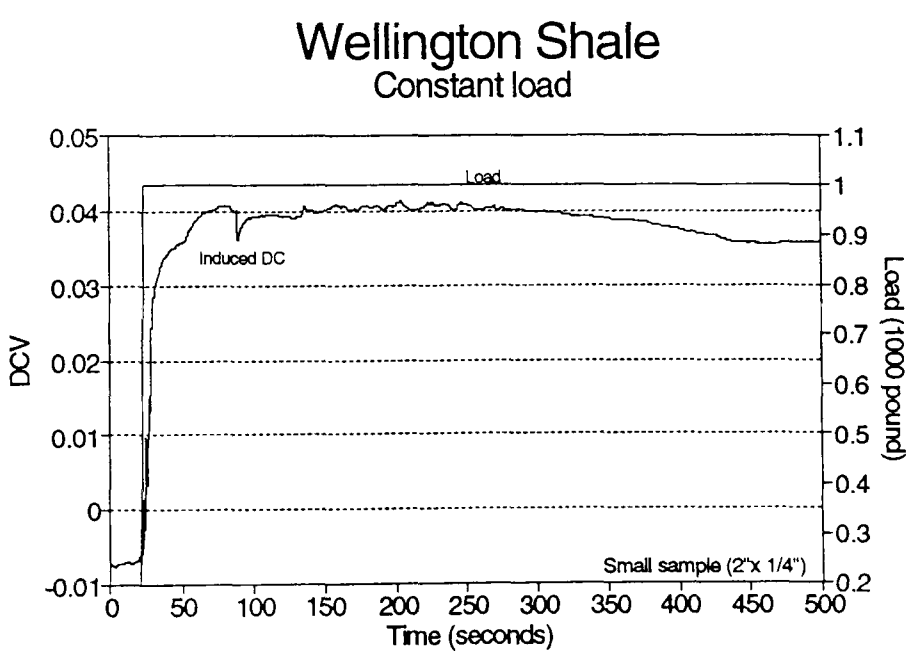


Figure 6.6 Induced DC on Small Wellington Shale

Figure 6.7 shows that the big sample took a longer time for the induced DC potential to reach the maximum magnitude after the maximum load was given on the sample. This may be because the ions have to travel farther from the center of the sample to the electrodes at the ends of the sample.

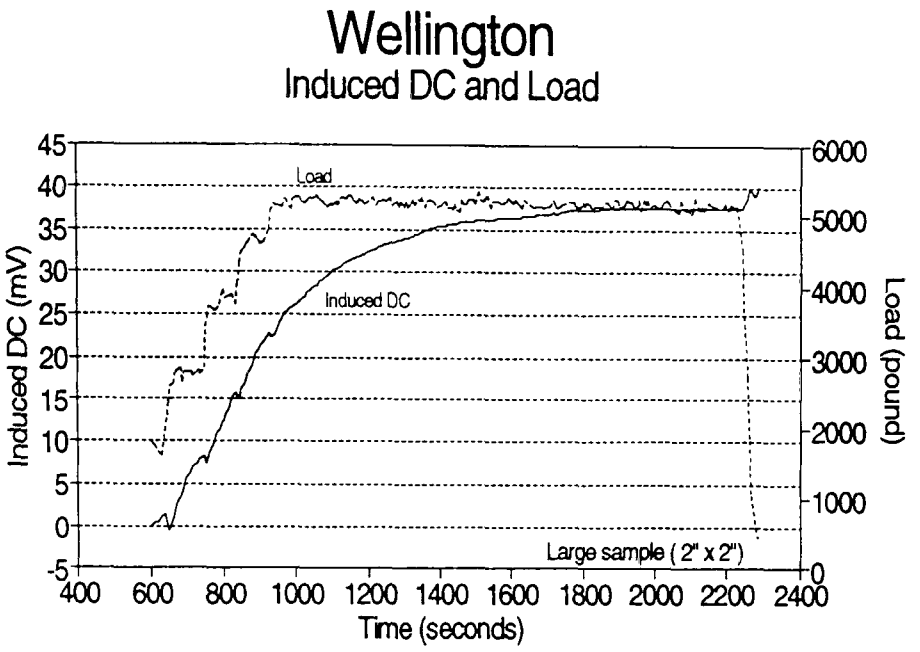


Figure 6.7 Induced DC on Big Wellington Shale

Figure 6.8 shows the induced DC potential of Wellington shale as a function of cyclic load. As shown on the plot, the induced DC is approximately in phase with loading and decreasing magnitude for the later loadings. This reduction in magnitude is due to the loss of water (thus also the movable ions) from the previous loadings. Also shown on the plot is the induced DC from a dry ceramic disc. The maximum load on both samples was 1500 lb.

A long-term observation of this induced DC potential showed that the effect of the induced DC potential completely vanished after 30 days.

Some potential applications of this induced DC phenomena are for determining the ion diffusion state through a time-lapse measurement, for determining the stress state at a particular location in the borehole, and as a diagnostic tool of the wellbore condition such as to detect the onset of wellbore instability due to shale swelling.

To help with data management while an experiment is underway, a computer routine for data acquisition has been developed. The routine controls a multiplexer box with its inputs connected to various instruments, and the output connected to a multimeter. The computer routine can also control a digitizing oscilloscope for acquiring acoustic travel time data. All controls and readings are through the GPIB (General Purpose Interface Bus)

to the controlling computer. Appendix A gives detailed instructions on how to set the measurement parameters and use the program.

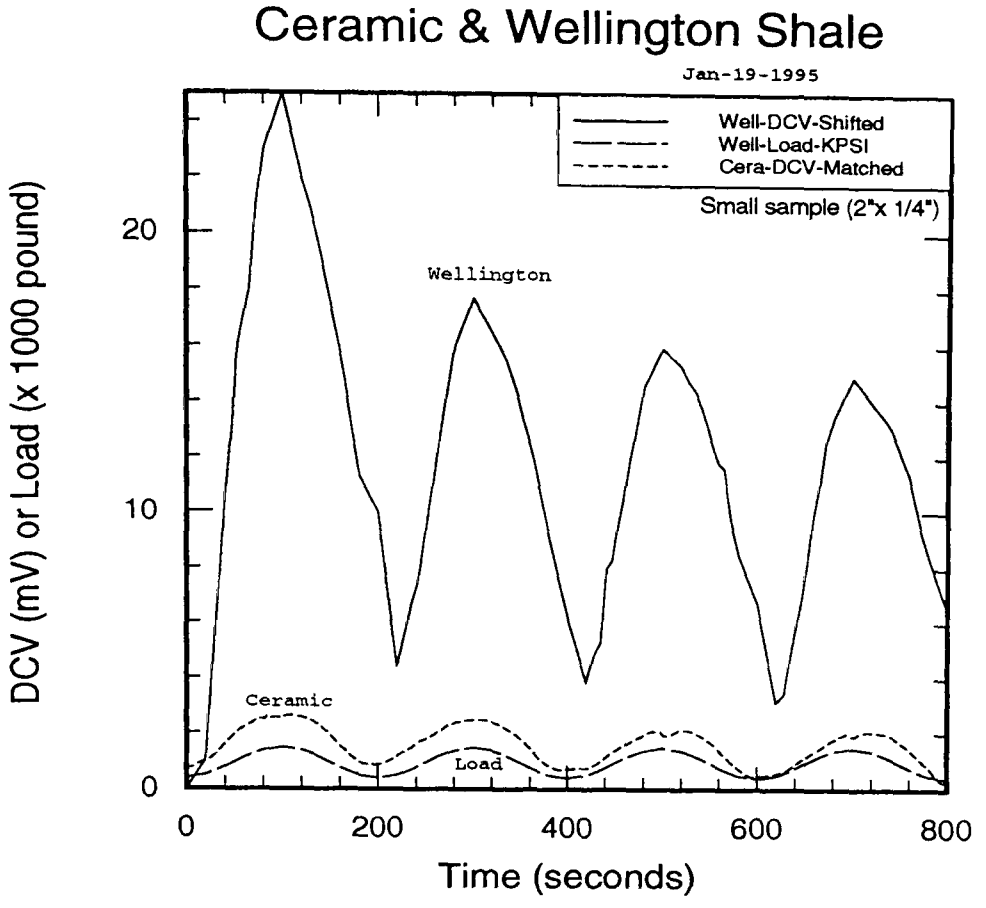


Figure 6.8 Shale and Ceramic Disc on Cyclic Loading

6.2 Shale as a Viscoelastic Medium

When a stress (pressure) is impressed on the shale, the matrix and pore fluid will bear the stress together. The rock matrix response is almost instantaneous in bearing the load. Pore fluid, on the other hand, due to restricted passage, will be squeezed out slowly as the medium is straining. Hence the stress-strain function varies with time; this media is called a *viscoelastic* media, as the media is not responding as a typical elastic media, e.g. steel, but like a viscous fluid, e.g., water.

Shale can be modelled as similar to spring and dashpot in parallel where the spring is the rock matrix and the dashpot is the pore fluid. This model was first proposed by Voigt in 1892 (Tschoegl, 1989) and is diagrammatically shown in Figure 6.9. Maxwell proposed another model for viscoelastic medium, where instead of parallel setup, the spring and the dashpot are in series, as shown in Figure 6.9b. In Maxwell solids, the sudden application of a load induces an immediate deflection by the elastic spring, which is followed by

"creep" of the dashpot. For the Voigt solid a sudden application of force will produce no immediate deflection because the dashpot, arranged in parallel with the spring, will not move instantaneously. Instead a deformation will gradually build up while the spring takes a greater and greater share of the load. The dashpot displacement relaxes exponentially.

(a) Voigt (b) Maxwell

Figure 6.9 Voigt and Maxwell Viscoelastic Models

In a step loading experiment, the shale sample is suddenly loaded with either a heavy brass load or by a load-frame piston. As the stress slowly propagates from the loaded side to the base side, pore fluid is squeezed out from the side with high stress, the loaded side. As pore water drains out, anions in the water also drain out and pile up at the sample-electrode interface, creating an excess negative charge on the loaded side. This explanation supports the actual observations that show the loaded side as more negative than the base side. The induced DC potential reaches the maximum point as soon as the stress distributes evenly across the length of the core. A longer sample will make a longer propagation time, as confirmed in Figure 6.7. This figure shows that ramping up time is longer for a 2 inch long sample than the short (1/4 inch) sample, as shown in Figure 6.6. After the stress distributes evenly, the dashpot displacement will vanish exponentially as shown on the decay on Figure 6.3.

In cyclic loading, the pore fluid movement can keep up with the loading rate; hence, on the uploading side the potential is in sync with the load, but this pore fluid movement

can not change direction on the sudden change in stress direction in the beginning of the downloading side, as can seen by the lag (slightly bulging line) on download sides in Figure 6.8. The exponential decay on cyclic loading can be seen on the maximum values of DC potential that drops with increasing cycle, shown in Figure 6.8.

In conclusion, by modeling shale as viscoelastic medium, the induced DC potential that is generated from the sample while under stress can be reasonably explained, and by studying the ramp-up time, the sample length can be qualitatively approximated.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary

Two methods of sample cutting have been developed with the aim to produce sample discs as perfect as possible in order to minimize the time taken to manually sand and lap the sample surface after cutting. This improvement in sample cutting shortens the typical sample preparation from several days of manual labor to several minutes of light sanding.

To ensure that the samples will be fully saturated, or that no void space exists inside the sample, all samples were oven-dried to move all the water out. The samples were then placed inside desiccators with increasing humidity to slowly bring back the pore water. This is a very slow process as one sample typically takes around 1 month to get back to its native condition. A combination of acoustic and electromagnetic measurement methods have been developed to find whether a sample has void space or not.

Work to find the best preservation fluid from several fluids has been done with the objective of a short term usage, to preserve the sample's pore water during the electromagnetic properties are measured. Another application is for long term storage where the sample's properties need to stay intact.

Three methods for changing water saturation inside the sample have been used to control the amount of water inside the sample while acquiring its electromagnetic properties: the desiccator, electro-osmosis, and air evaporation methods.

The electromagnetic measurement of this study, from 5 Hz up to 1.3 GHz, spans almost half of the currently available measurement capability and covers all logging tool frequencies that are currently available, so the outcome of this research can be easily applied to field operation.

This research found that while a shale sample is under stress, the movement of pore water will generate an electrical current, called Induced DC potential, that is linear with the stress magnitude and decays with time.

7.2 Conclusions

The conclusions reached in this dissertation are summarized in the following points:

- The improved sample cutting procedure creates better samples with a shorter preparation time.
- Sample weight decreases linearly with air exposure time.
- Equilibration time of shale after 5 minutes of air evaporation is around 2 hours.
- Several preservation fluids that have been tested on the shales allowed pore waters and ions to move out from the sample.
- Several results that have been observed from the electro-osmosis experiment are as follows: (1) water moves toward the cathode end as predicted; (2) the change in water content can be detected more easily at the lower frequencies; and (3) the change of water content is not always reflected by a change of conductivity/susceptivity at that particular location, but by changes at neighboring samples.
- Several results from the electromagnetic experiment are as follows: (1) conductivity and dielectric constant drop with increasing water loss; (2) the changes in conductivity can be seen more at the lower frequencies than at higher frequency; (3) the location and magnitude of the dissipation factor decreases as water loss increases; (4) by comparing the dissipation factor characteristic from different well-logs on the same formation type, the formation water saturation can be qualitatively approximated; (5) dissipation factor characteristics from MWD tools can be displayed at the drill floor in real time and can be used to predict the onset of wellbore instability; and (6) to be able to use the dissipation factor method for detecting the changes in shales' water content, well logging tools and MWD tools need to be modified to work at low frequencies and to be of variable frequency.

- Several results from the Induced DC potential experiment on shale as follows: (1) the magnitude is linear with the given stress; (2) the potential decays exponentially with time, which can be explained by modeling the shale as a viscoelastic media; (3) the ramping-up time can be related with sample thickness, and (4) this phenomenon can be used for a diagnostic tool to detect changes of stress around the wellbore such as for detecting the onset of wellbore instability in shaly formations.

7.3 Recommendations for Future Works

A better preservation fluid needs to be found as this fluid is important for long term storage of shale samples and also for short term immersion during the electromagnetic measurement where the sample's water content needs to be constant while the reading is taken. To better understand the pore water and ion movement from shale to the preservation fluid, an ion analysis needs to be done on the confinement fluid. The candidate for a good preservation fluid should have the following characteristics: inert, non-hazardous, very low in water solubility, non-reactive to shale, high viscosity and inexpensive.

To enhance the result, another measurement method / equipment needs to be used to close the gap in the measurement frequency of 13 MHz and 20 MHz. Also, more shale samples need to be measured, especially from different clay compositions. A study for the case of increasing water content on shale also needs to be done.

To better understand the in-situ electromagnetic properties of shale, the measurement needs to be done at downhole temperature and/or pressure, something that is very difficult to attain with the current laboratory equipment without sacrificing the frequency range.

Induced DC potential needs to be analyzed more thoroughly with more samples of varying shale composition and also with various fluids that are in contact with the sample. This phenomenon can be developed into a practical knowledge at the well site to quickly determine wellbore stability condition.

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APPENDIX A

ELECTRICAL PROPERTIES OF WELLINGTON SHALE AT LOGGING TOOL FREQUENCIES

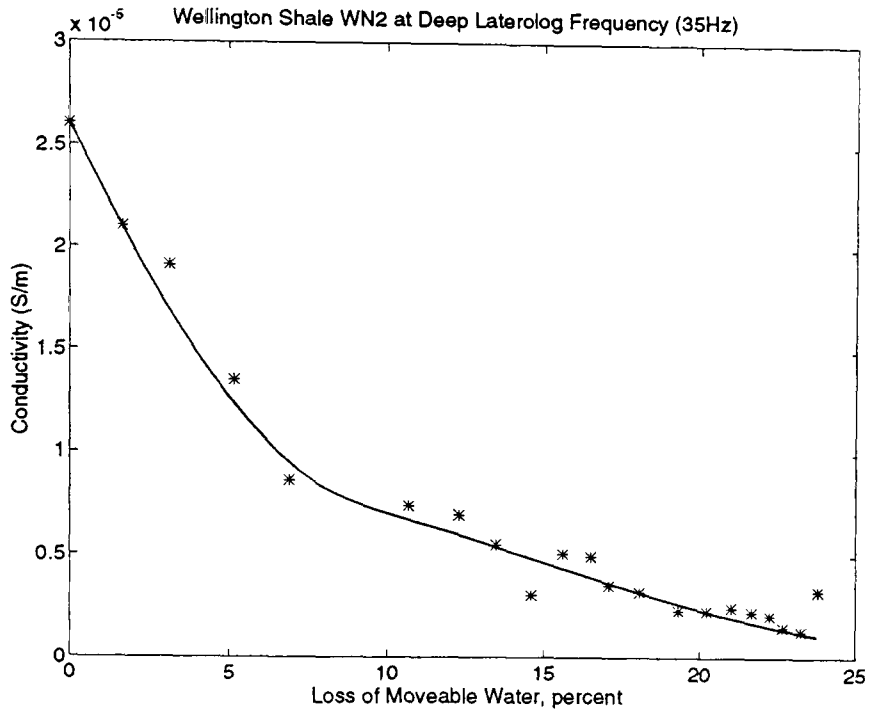

Figure A.1 Conductivity of Wellington WN2 at 35 Hz as a Function of Water Loss

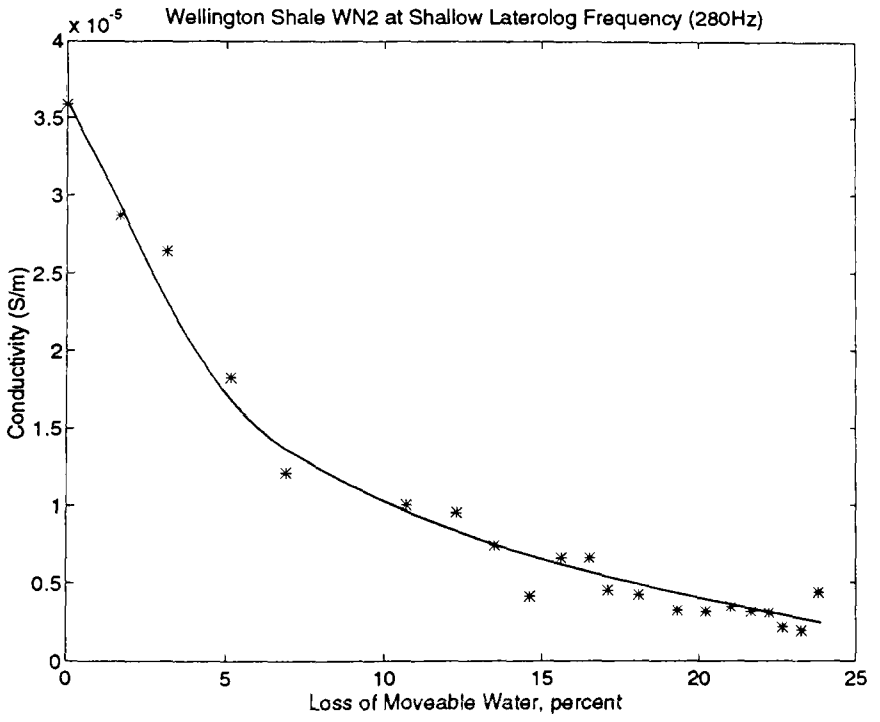

Figure A.2 Conductivity of Wellington WN2 at 280 Hz as a Function of Water Loss

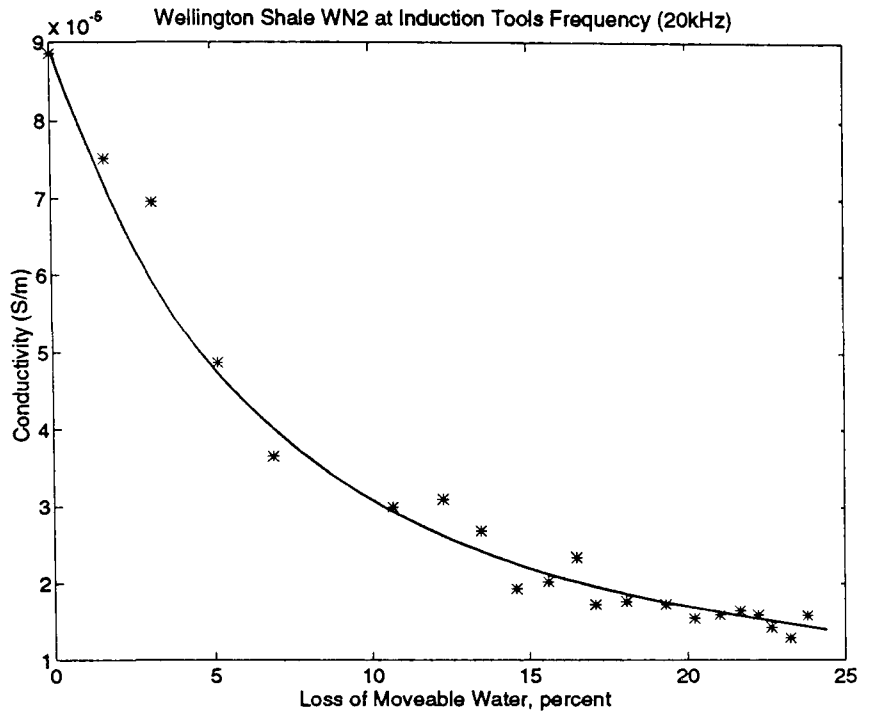

Figure A.3 Conductivity of Wellington WN2 at 20 kHz as a Function of Water Loss

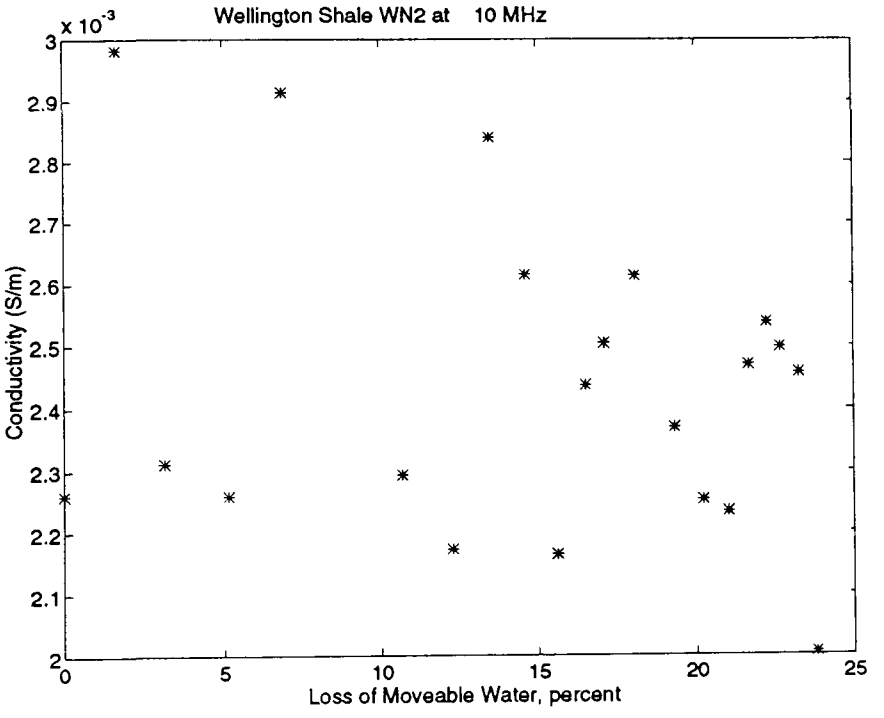

Figure A.4 Conductivity of Wellington WN2 at 10 MHz as a Function of Water Loss

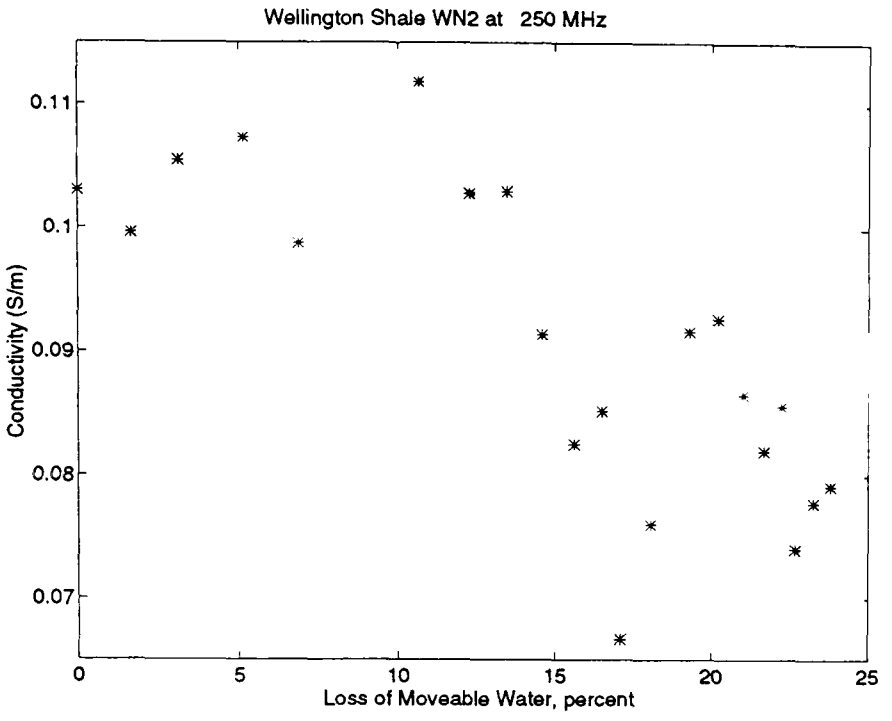

Figure A.5 Conductivity of Wellington WN2 at 250 MHz as a Function of Water Loss

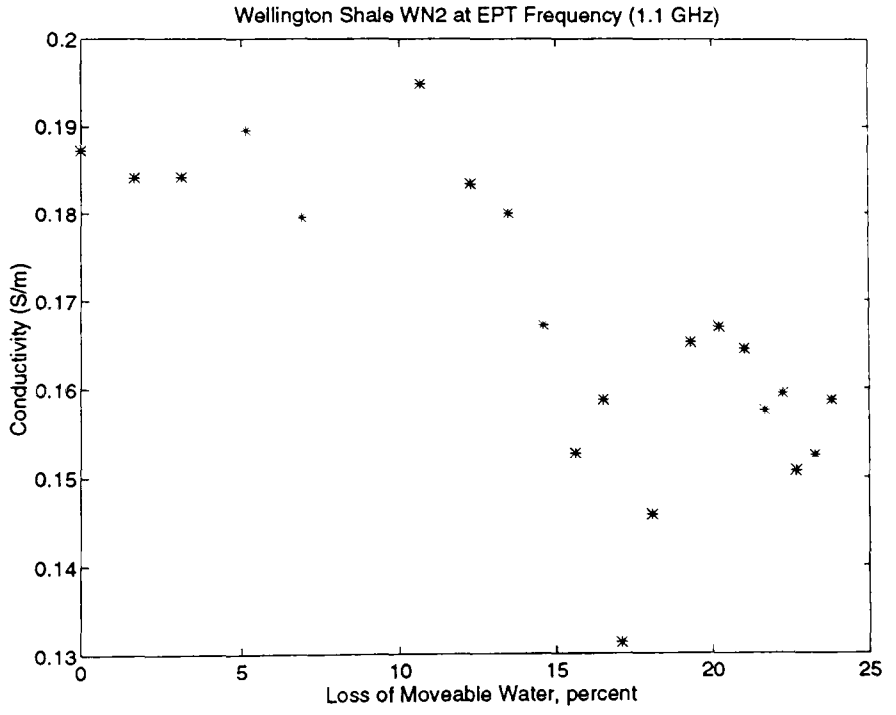

Figure A.6 Conductivity of Wellington WN2 at 1.1 GHz as a Function of Water Loss

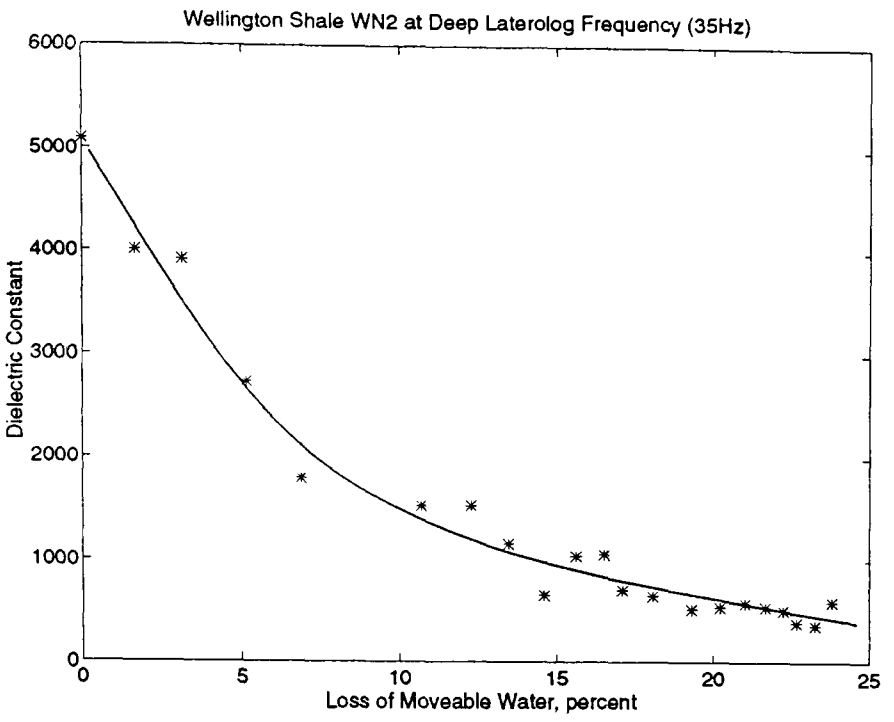

Figure A.7 Dielectric Constant of Wellington WN2 at 35 Hz as a Function of Water Loss

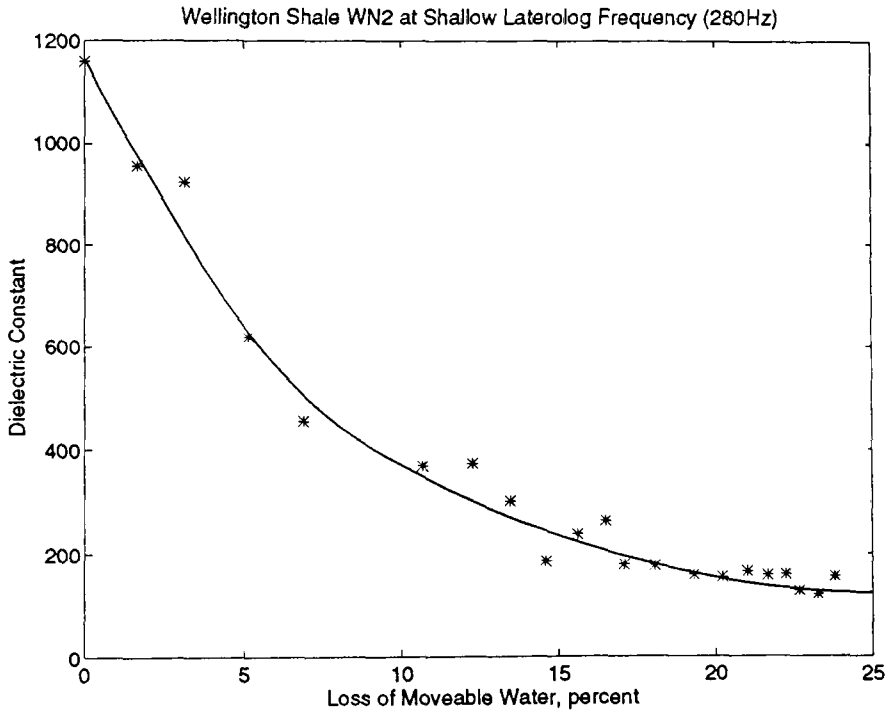

Figure A.8 Dielectric Constant of Wellington WN2 at 280 Hz as a Function of Water Loss

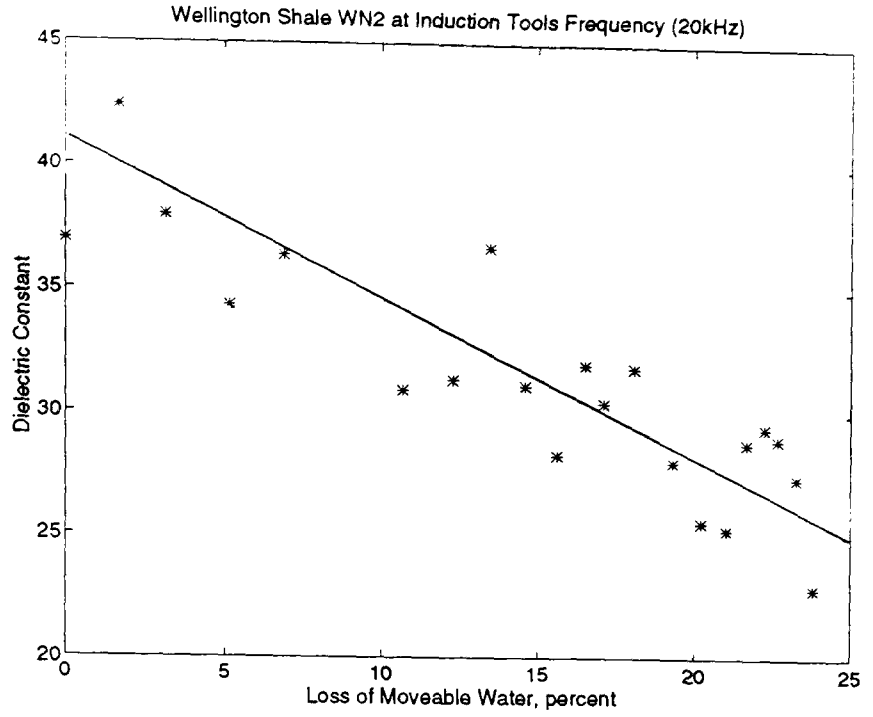

Figure A.9 Dielectric Constant of Wellington WN2 at 20 kHz as a Function of Water Loss

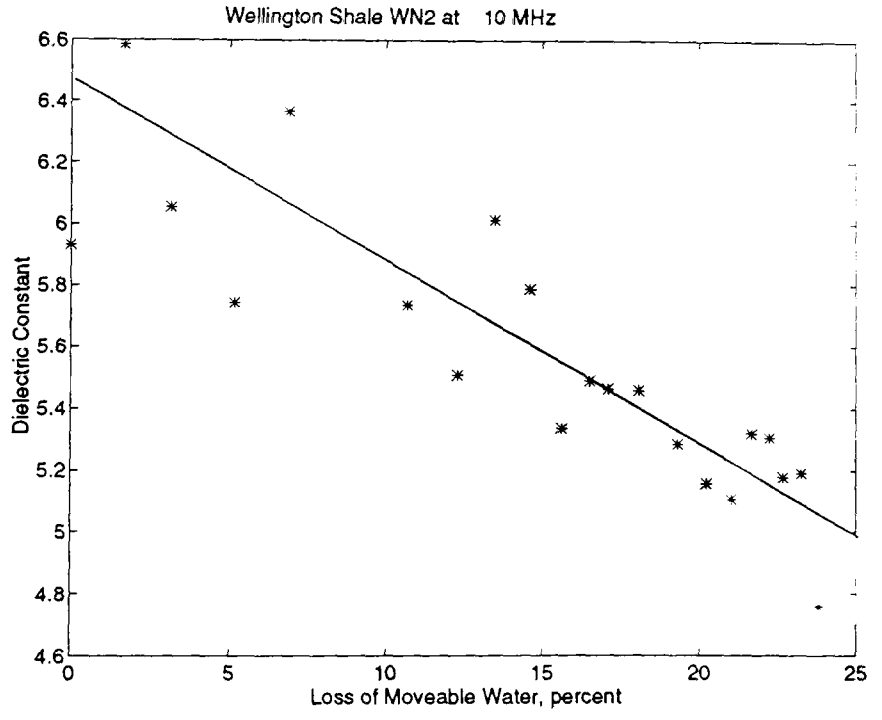

Figure A.10 Dielectric Constant of Wellington WN2 at 10 MHz as a Function of Water Loss

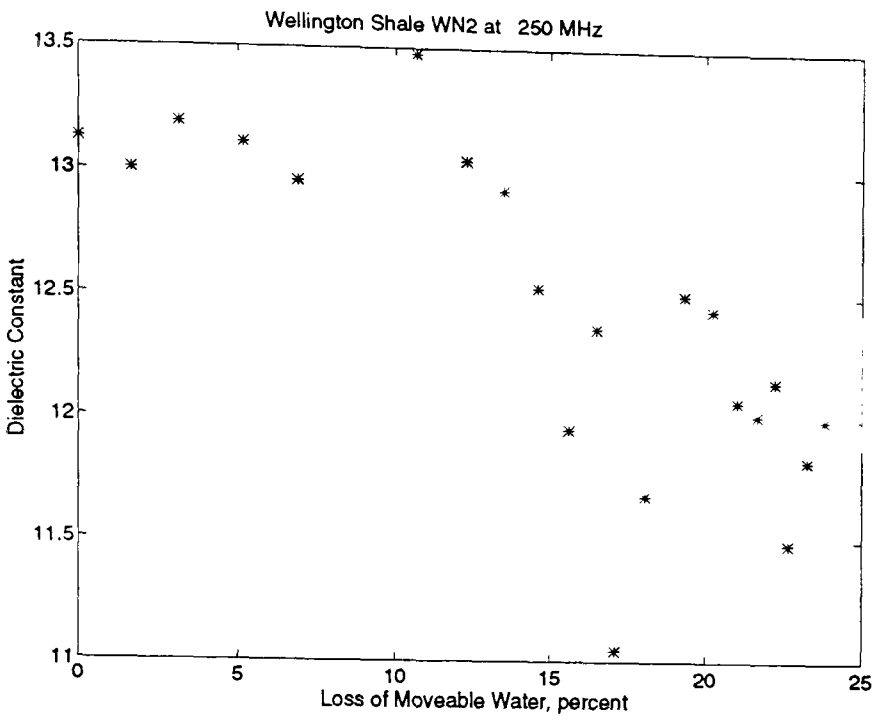

Figure A.11 Dielectric Constant of Wellington WN2 at 250 MHz as a Function of Water Loss

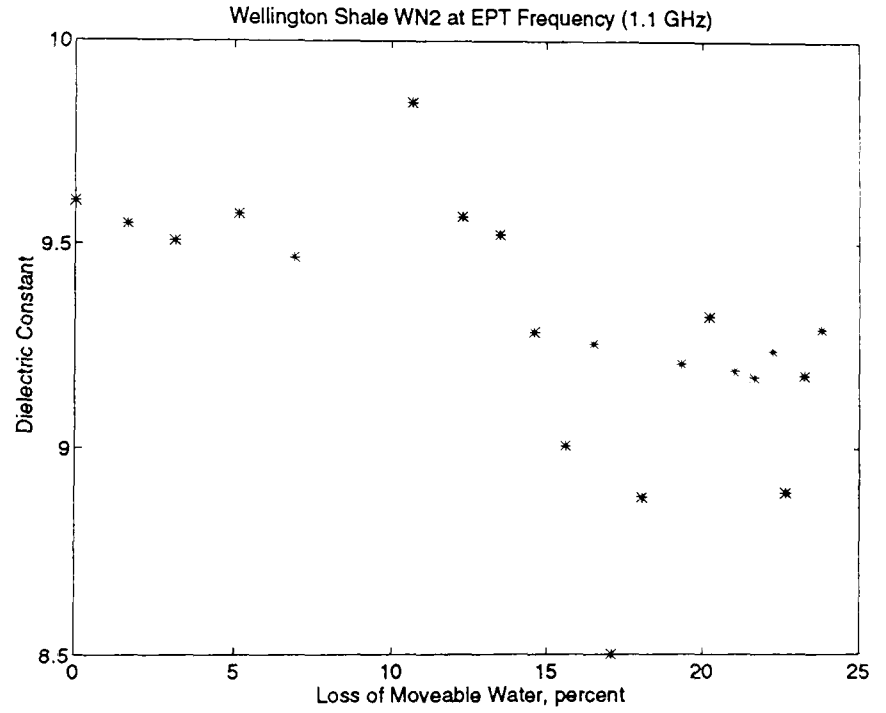

Figure A.12 Dielectric Constant of Wellington WN2 at 1.1 GHz as a Function of Water Loss

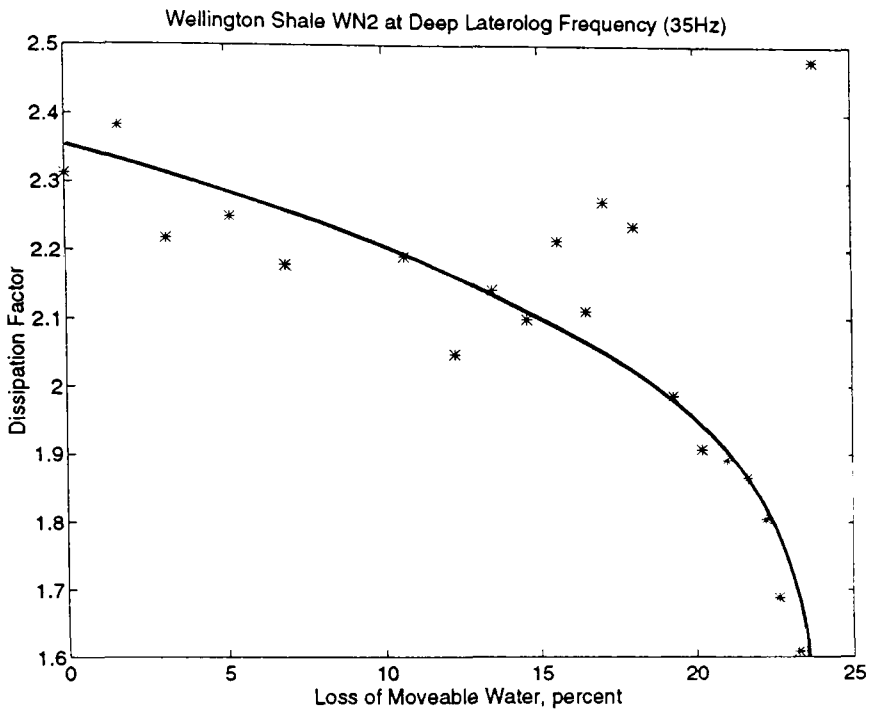

Figure A.13 Dissipation Factor of Wellington WN2 at 35 Hz as a Function of Water Loss

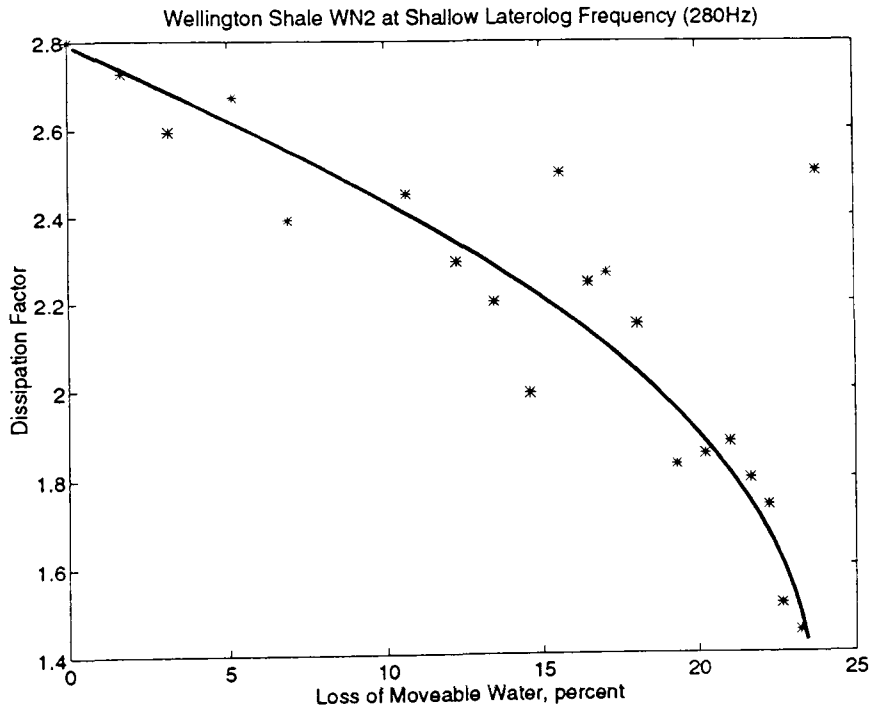

Figure A.14 Dissipation Factor of Wellington WN2 at 280 Hz as a Function of Water Loss

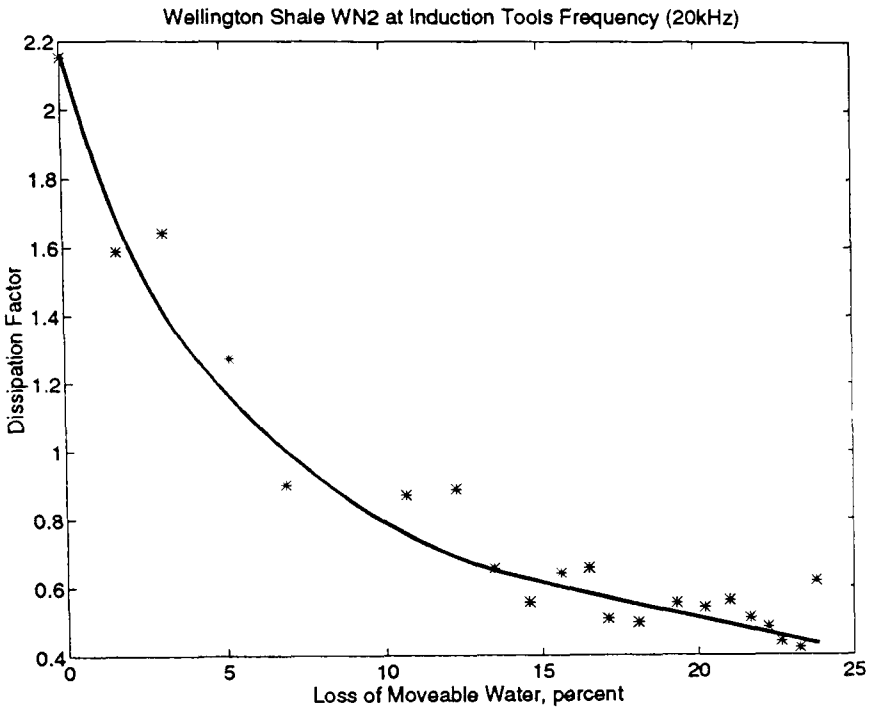

Figure A.15 Dissipation Factor of Wellington WN2 at 20 kHz as a Function of Water Loss

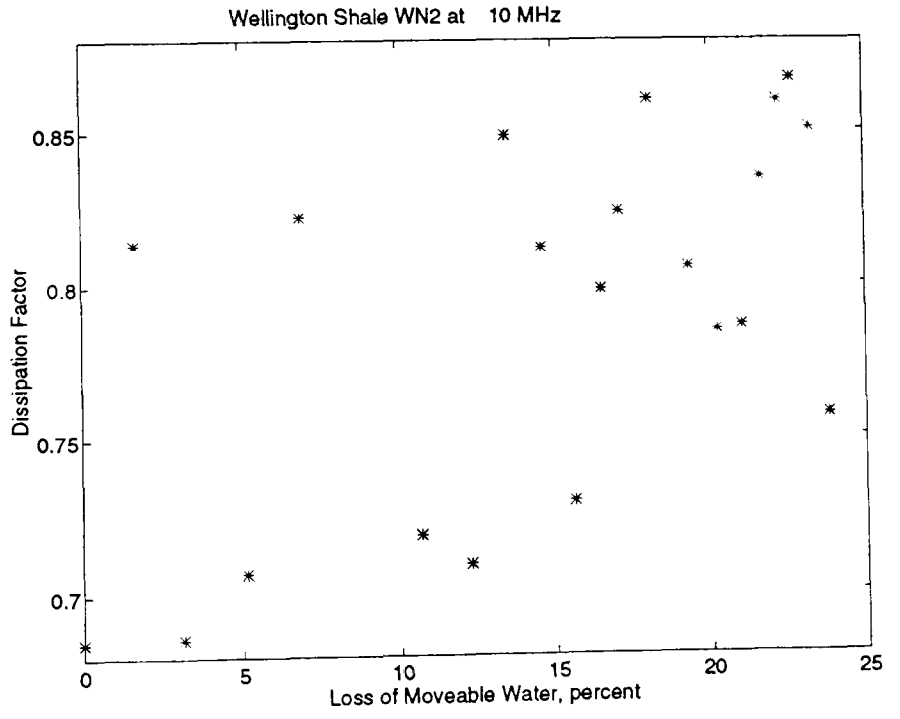

Figure A.16 Dissipation Factor of Wellington WN2 at 10 MHz as a Function of Water Loss

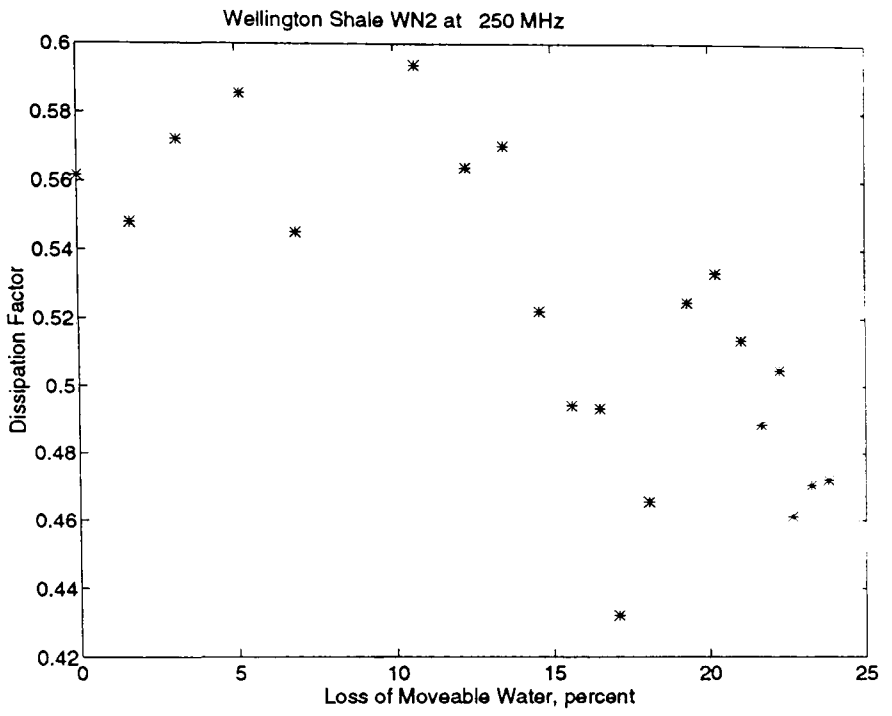

Figure A.17 Dissipation Factor of Wellington WN2 at 250 MHz as a Function of Water Loss

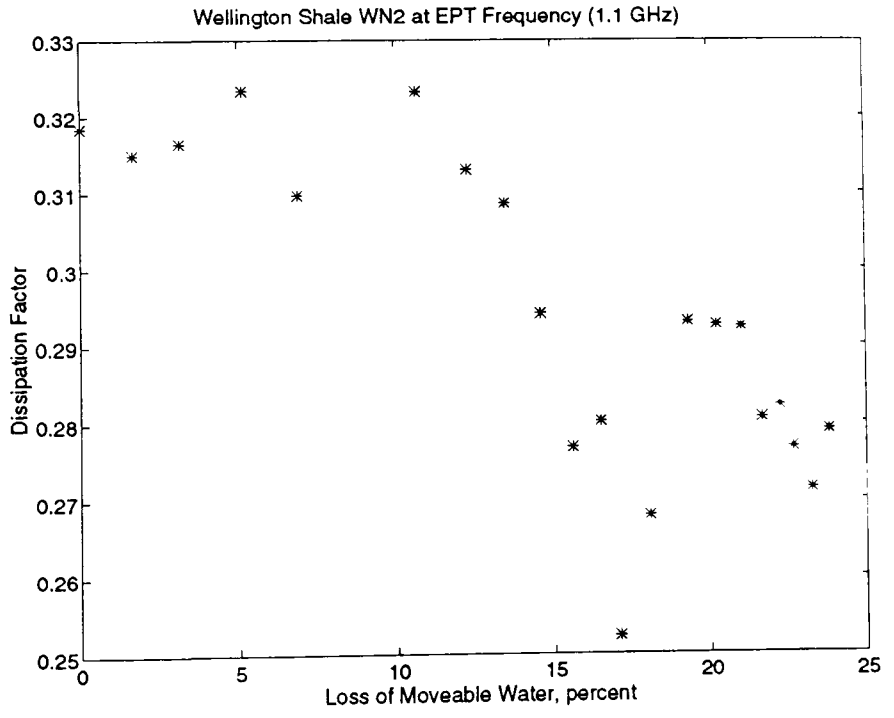

Figure A.18 Dissipation Factor of Wellington WN2 at 1.1 GHz as a Function of Water Loss

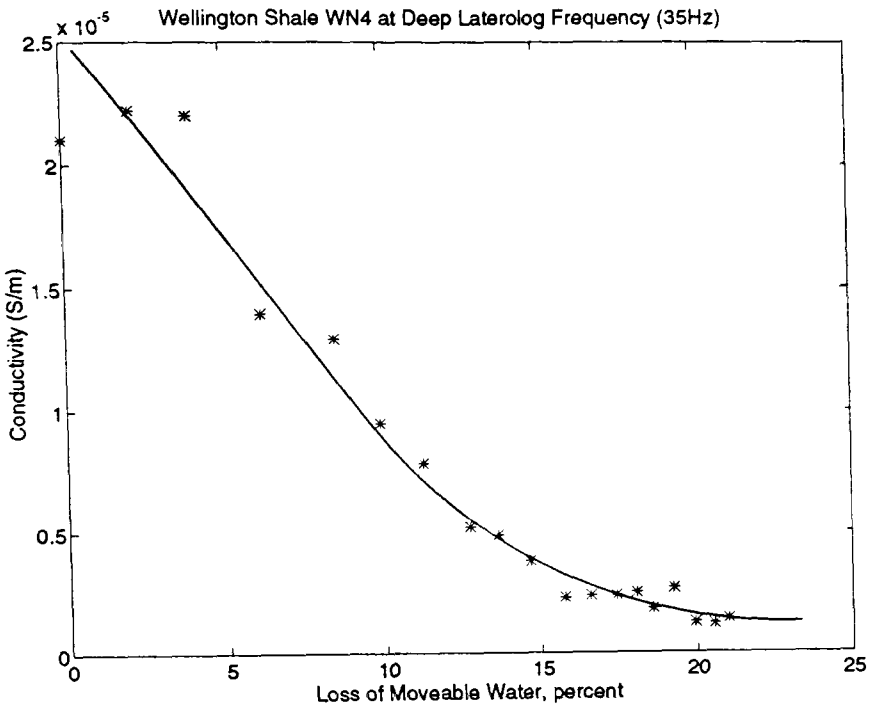

Figure A.19 Conductivity of Wellington WN4 at 35 Hz as a Function of Water Loss

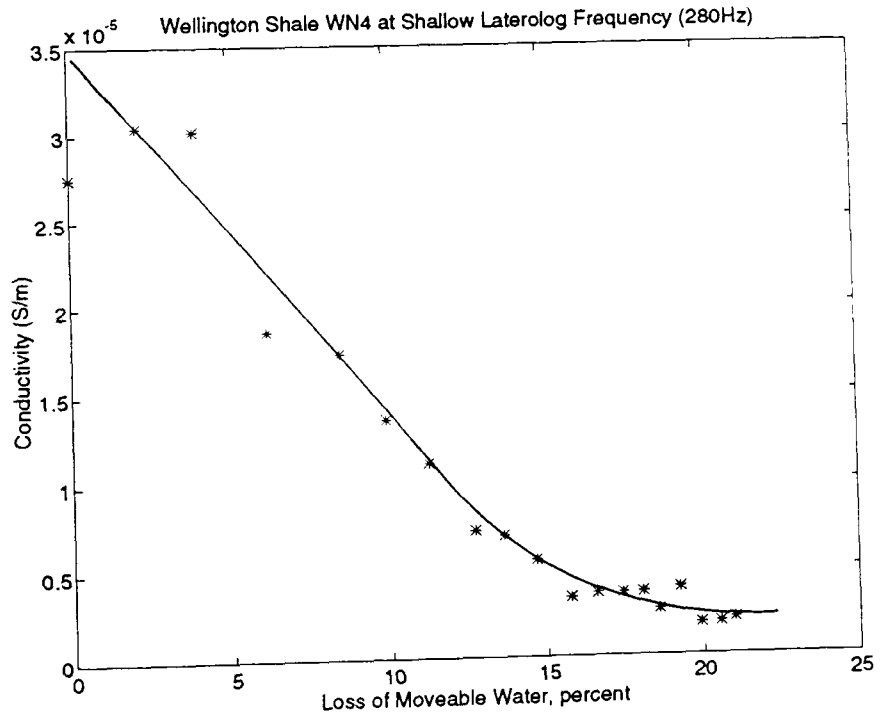

Figure A.20 Conductivity of Wellington WN4 at 280 Hz as a Function of Water Loss

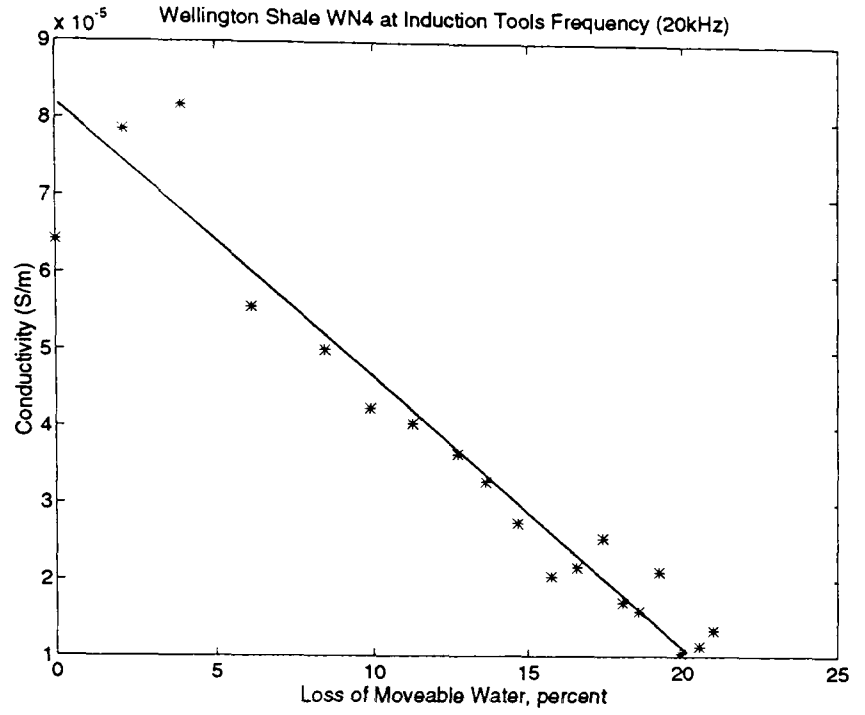

Figure A.21 Conductivity of Wellington WN4 at 20 kHz as a Function of Water Loss

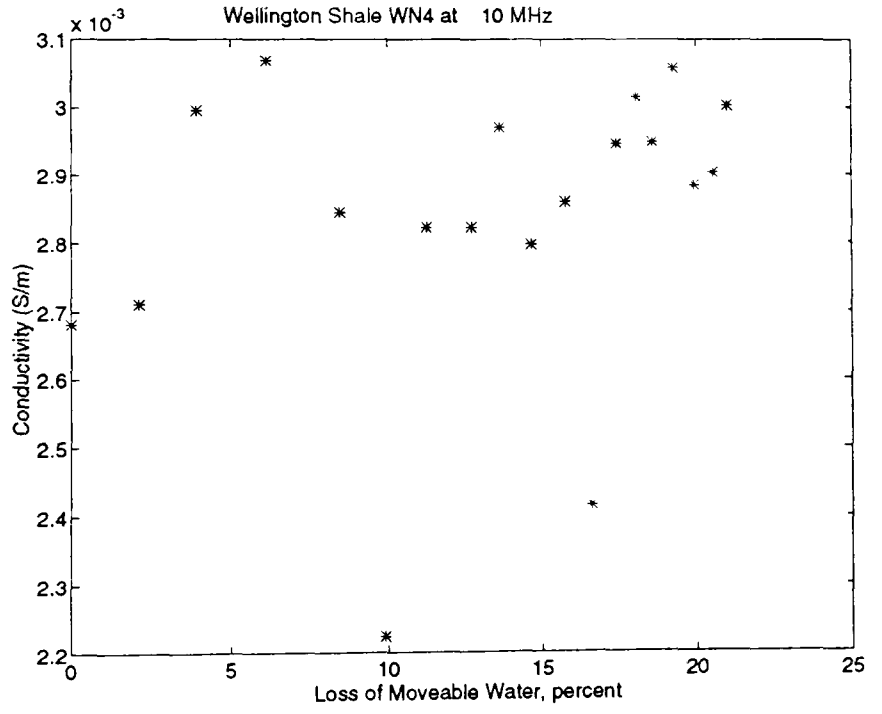

Figure A.22 Conductivity of Wellington WN4 at 10 MHz as a Function of Water Loss

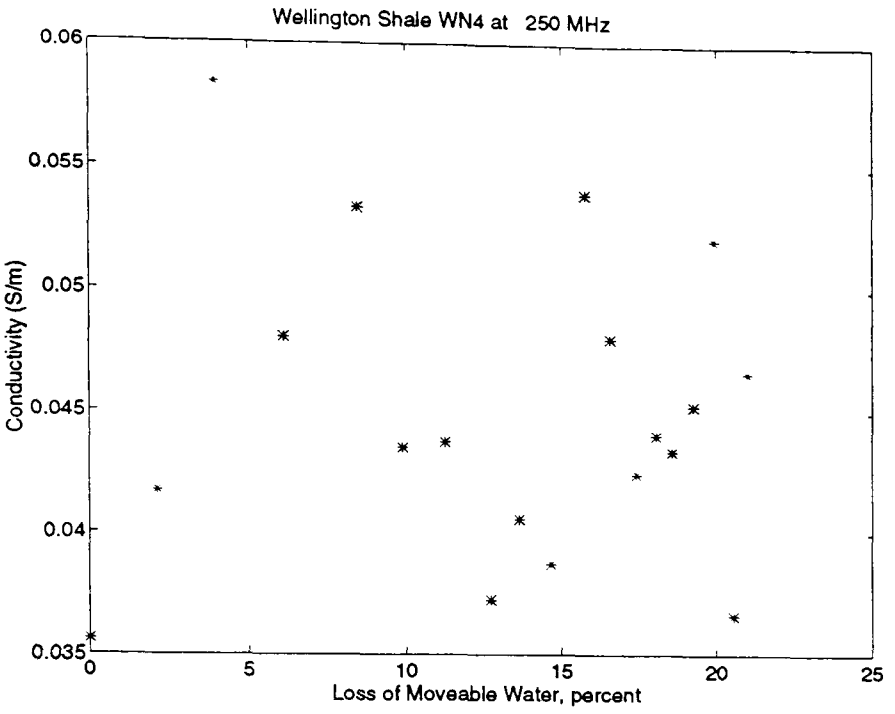

Figure A.23 Conductivity of Wellington WN4 at 250 MHz as a Function of Water Loss

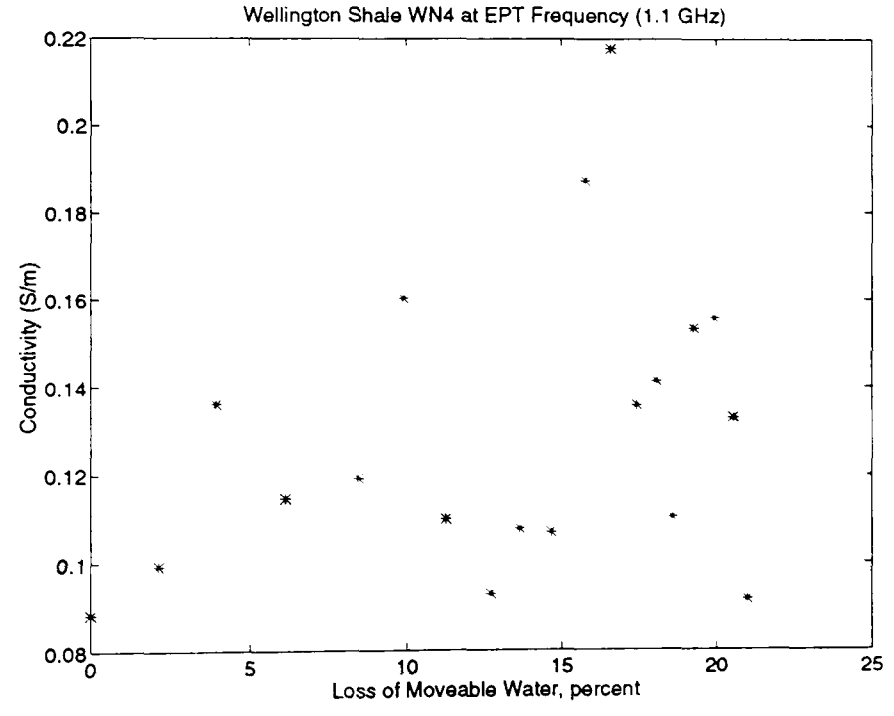

Figure A.24 Conductivity of Wellington WN4 at 1.1 GHz as a Function of Water Loss

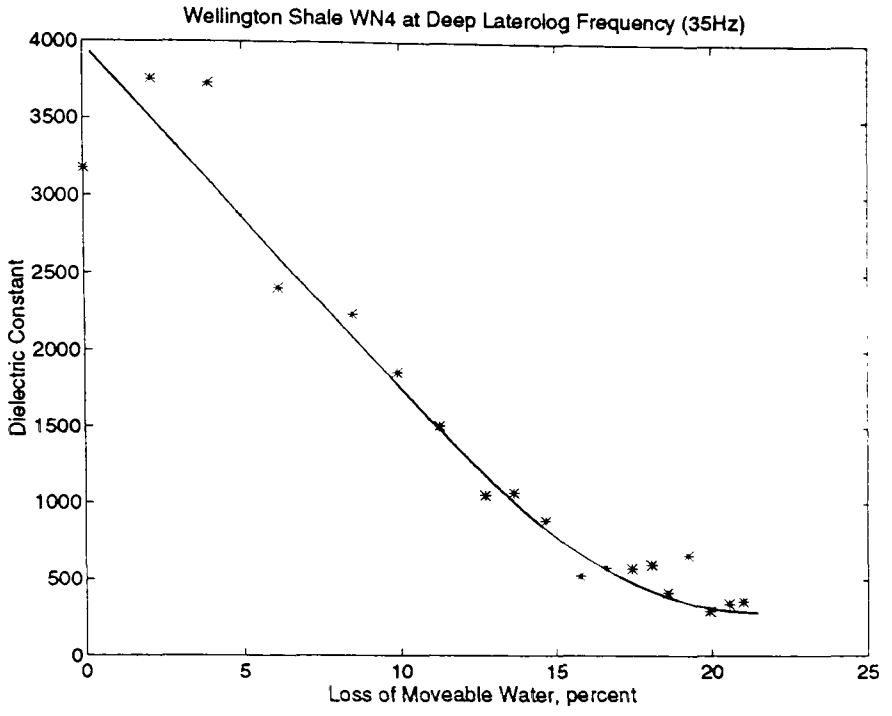

Figure A.25 Dielectric Constant of Wellington WN4 at 35 Hz as a Function of Water Loss

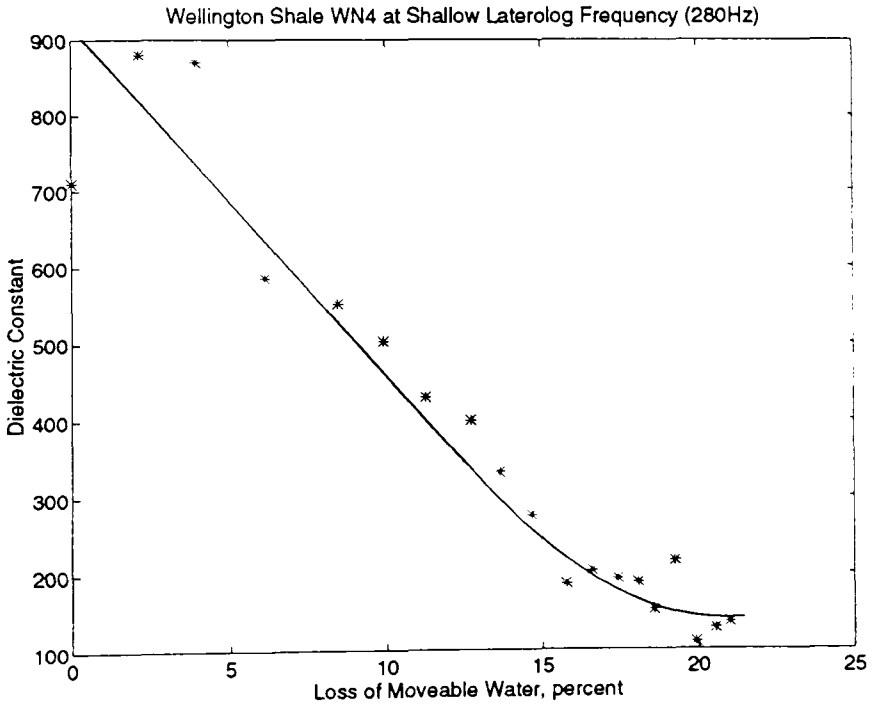

Figure A.26 Dielectric Constant of Wellington WN4 at 280 Hz as a Function of Water Loss

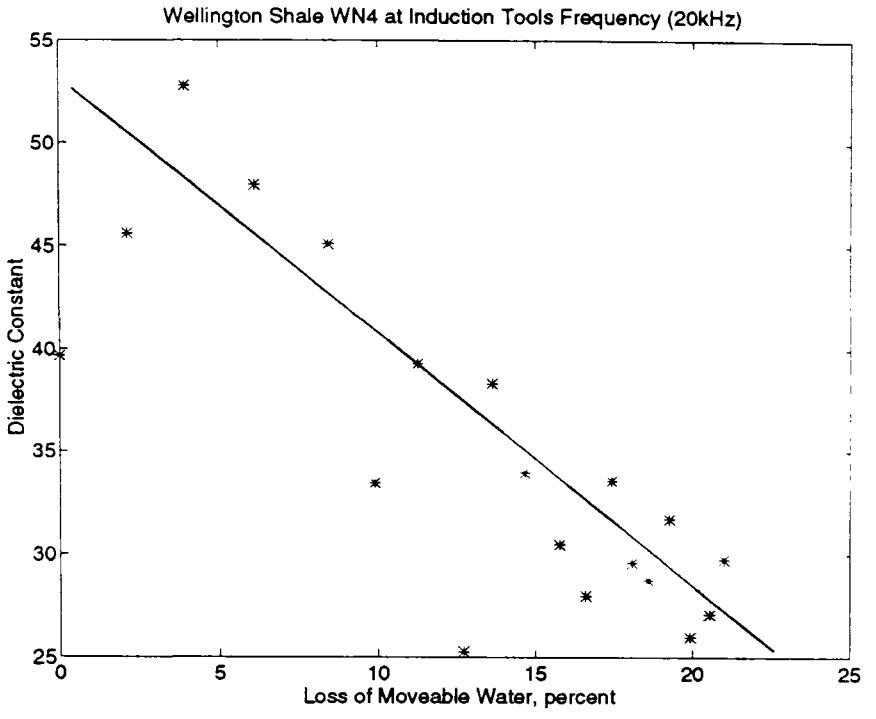

Figure A.27 Dielectric Constant of Wellington WN4 at 20 kHz as a Function of Water Loss

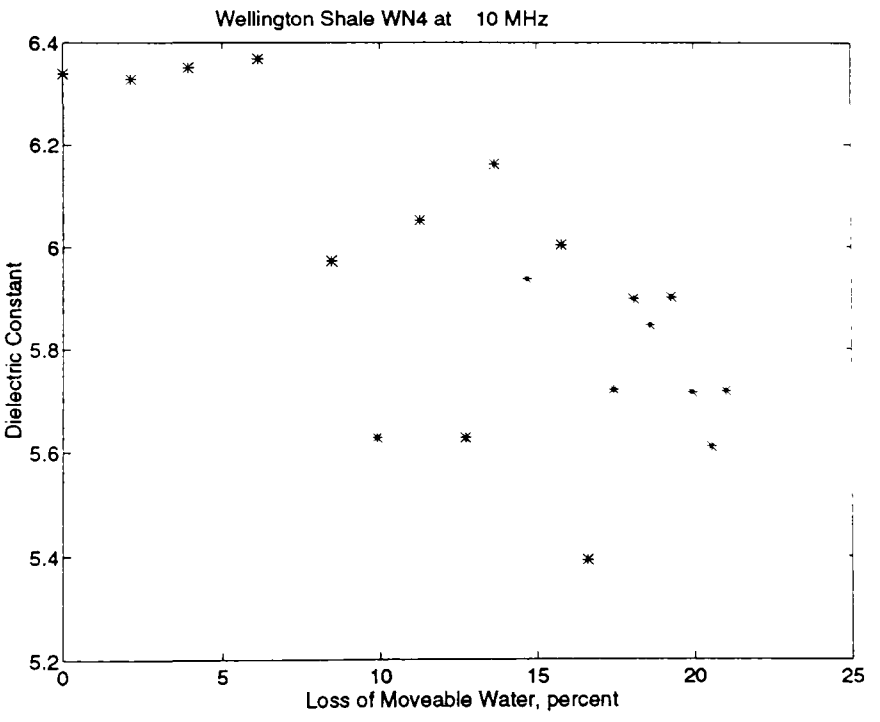

Figure A.28 Dielectric Constant of Wellington WN4 at 10 MHz as a Function of Water Loss

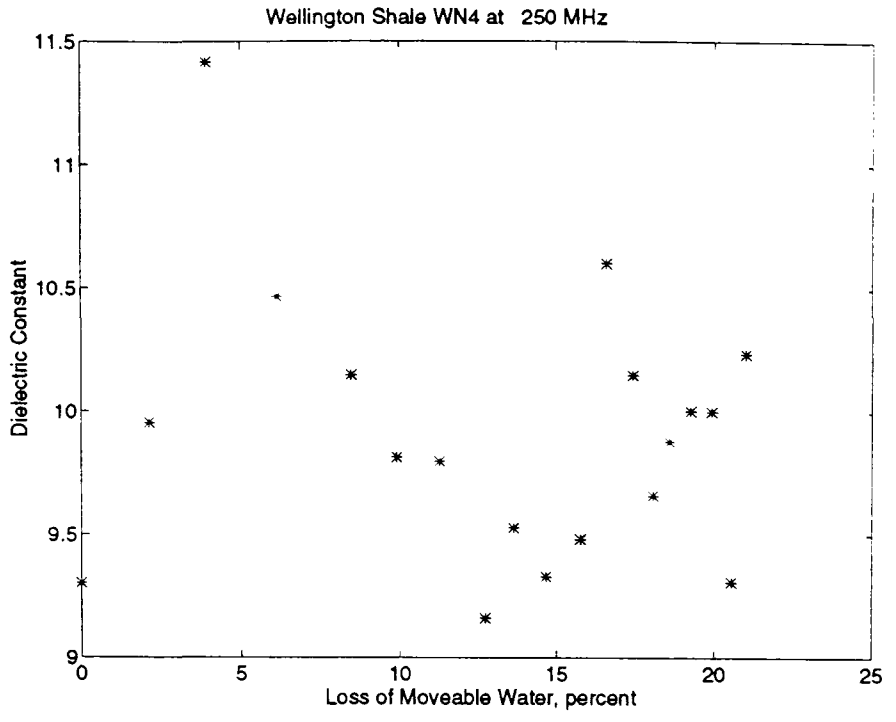

Figure A.29 Dielectric Constant of Wellington WN4 at 250 MHz as a Function of Water Loss

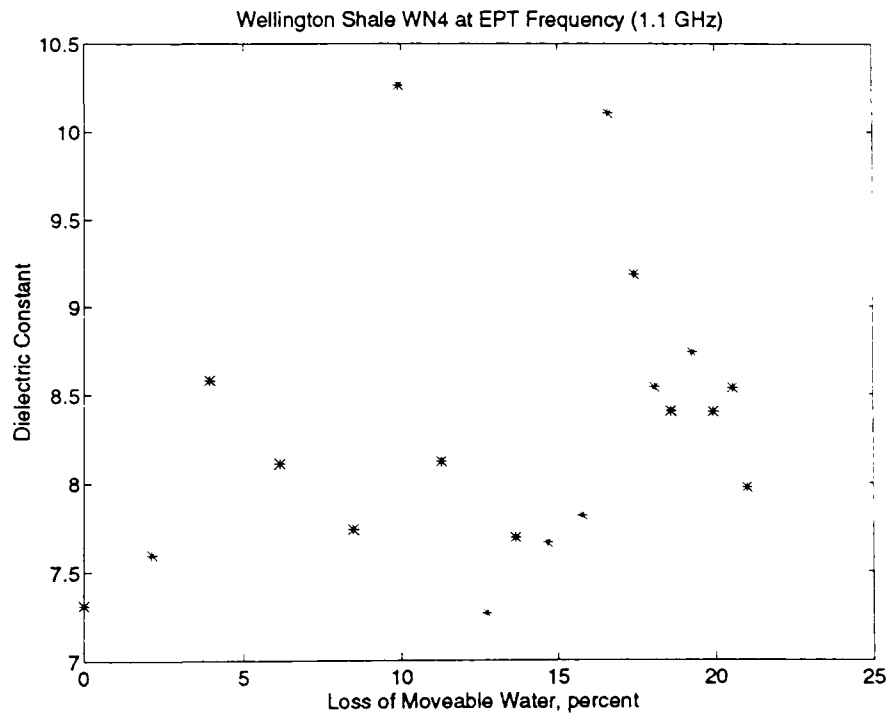

Figure A.30 Dielectric Constant of Wellington WN4 at 1.1 GHz as a Function of Water Loss

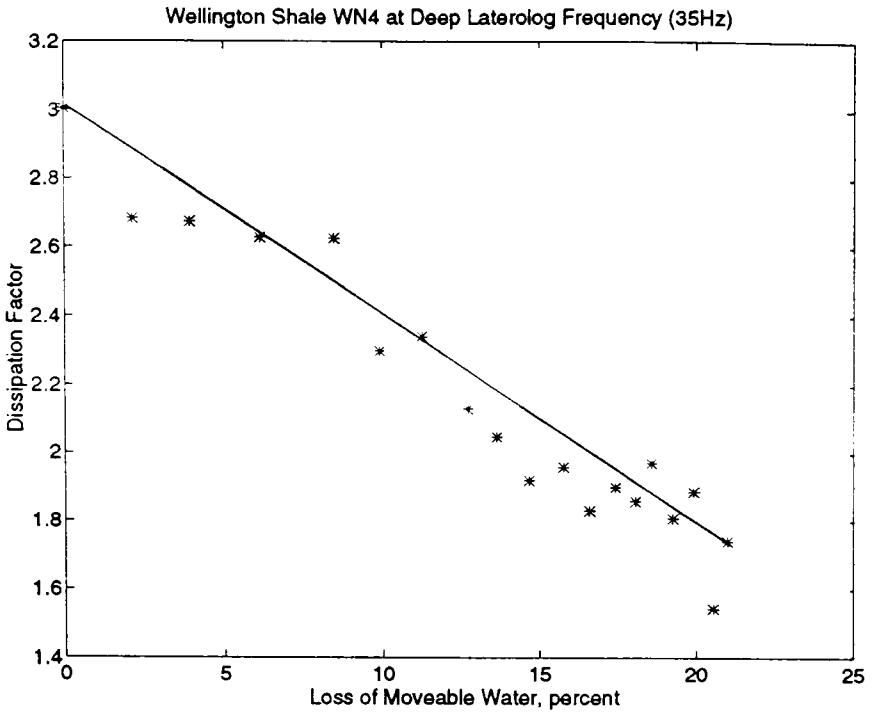

Figure A.31 Dissipation Factor of Wellington WN4 at 35 Hz as a Function of Water Loss

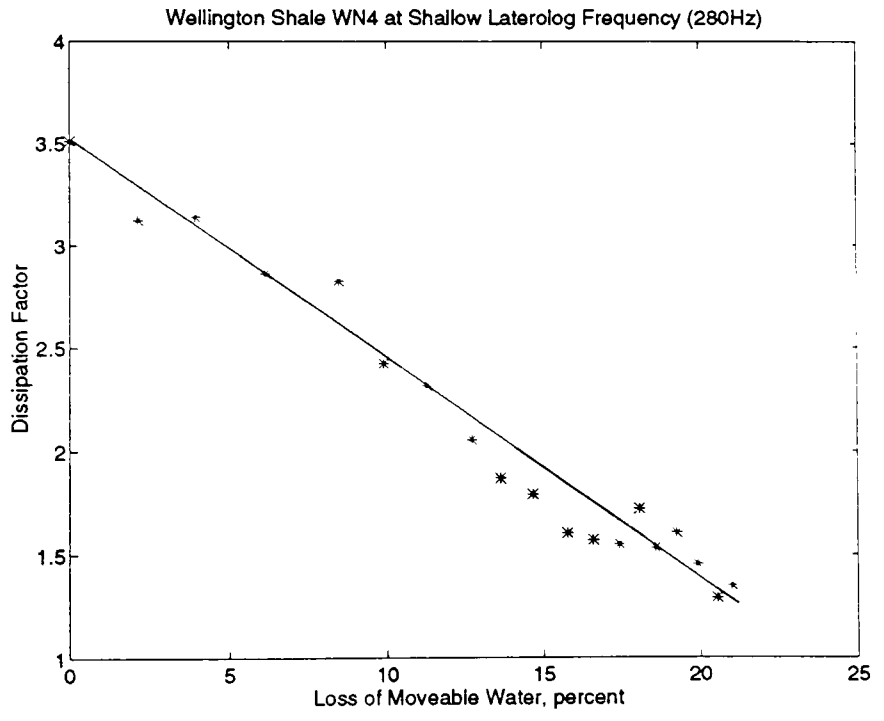

Figure A.32 Dissipation Factor of Wellington WN4 at 280 Hz as a Function of Water Loss

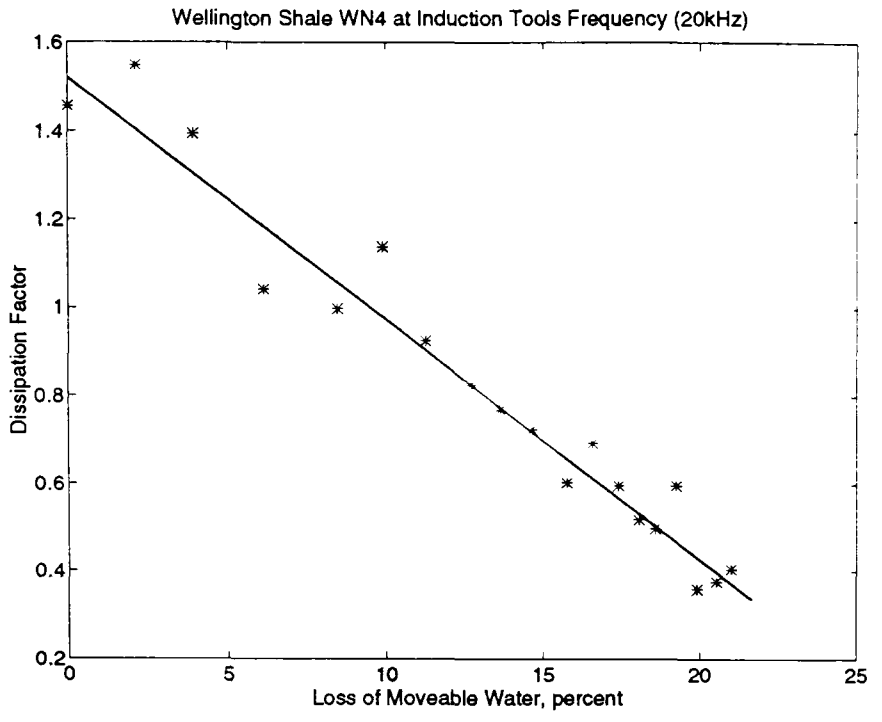

Figure A.33 Dissipation Factor of Wellington WN4 at 20 kHz as a Function of Water Loss

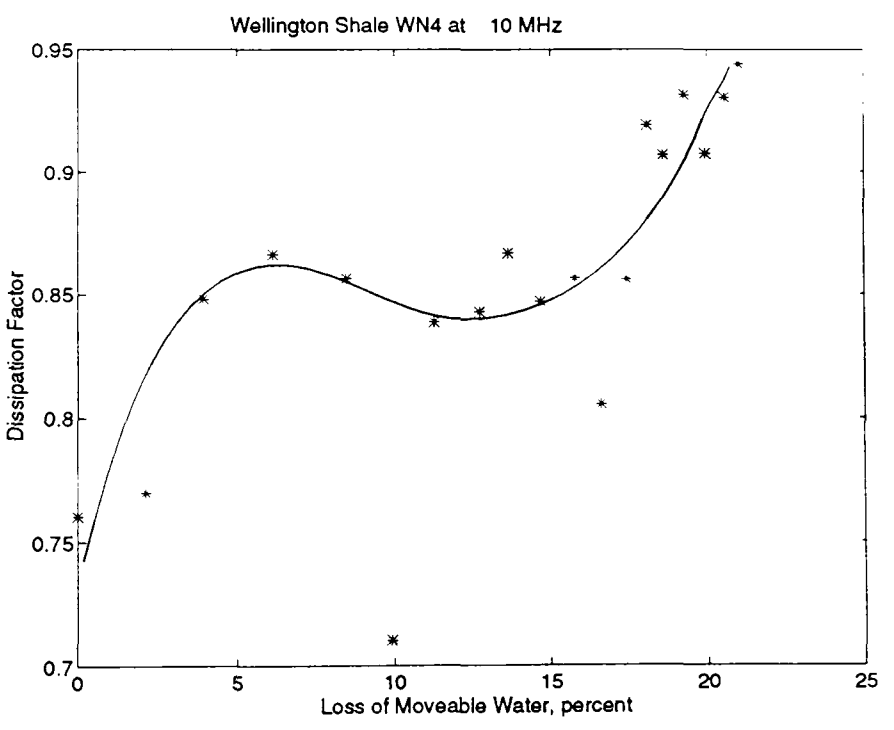

Figure A.34 Dissipation Factor of Wellington WN4 at 10 MHz as a Function of Water Loss

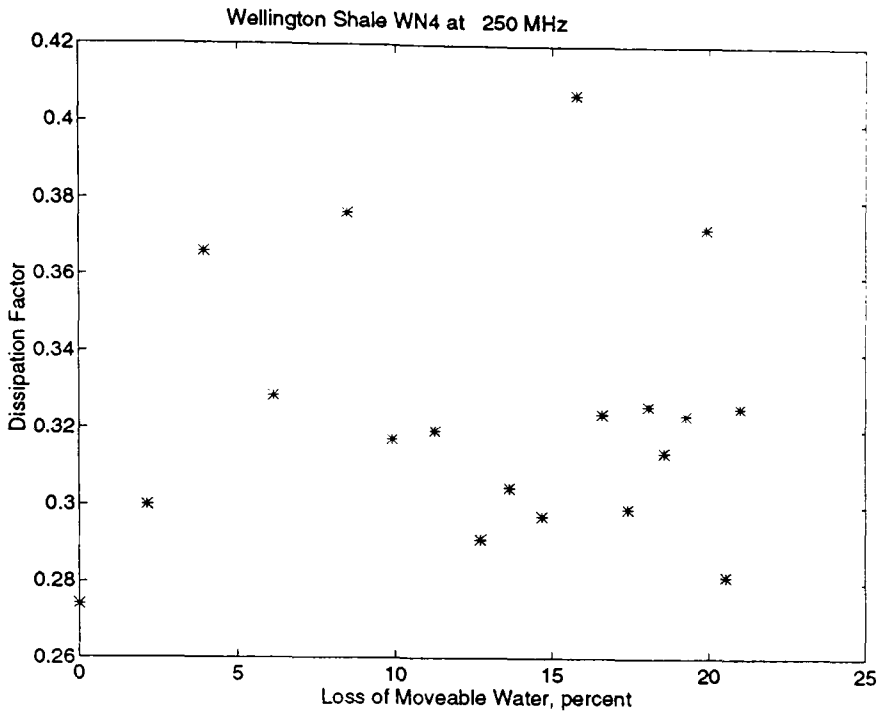

Figure A.35 Dissipation Factor of Wellington WN4 at 250 MHz as a Function of Water Loss

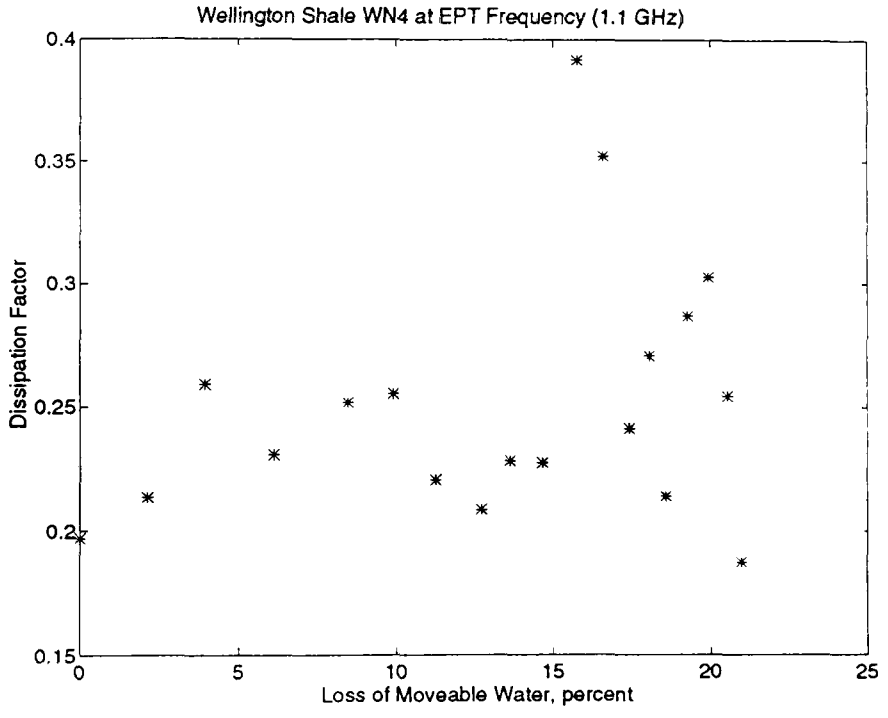

Figure A.36 Dissipation Factor of Wellington WN4 at 1.1 GHz as a Function of Water Loss

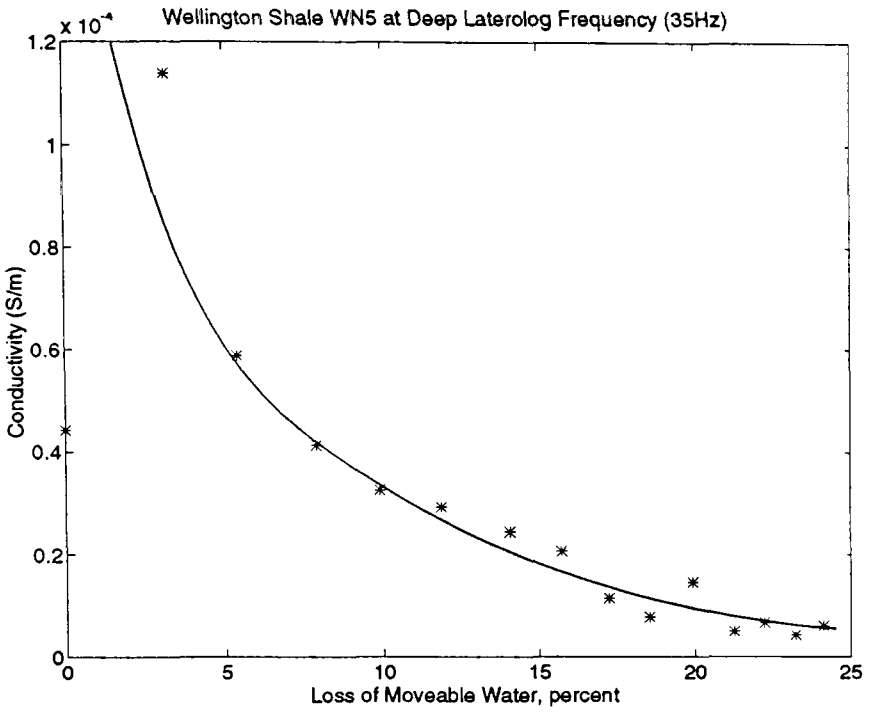

Figure A.37 Conductivity of Wellington WN5 at 35 Hz as a Function of Water Loss

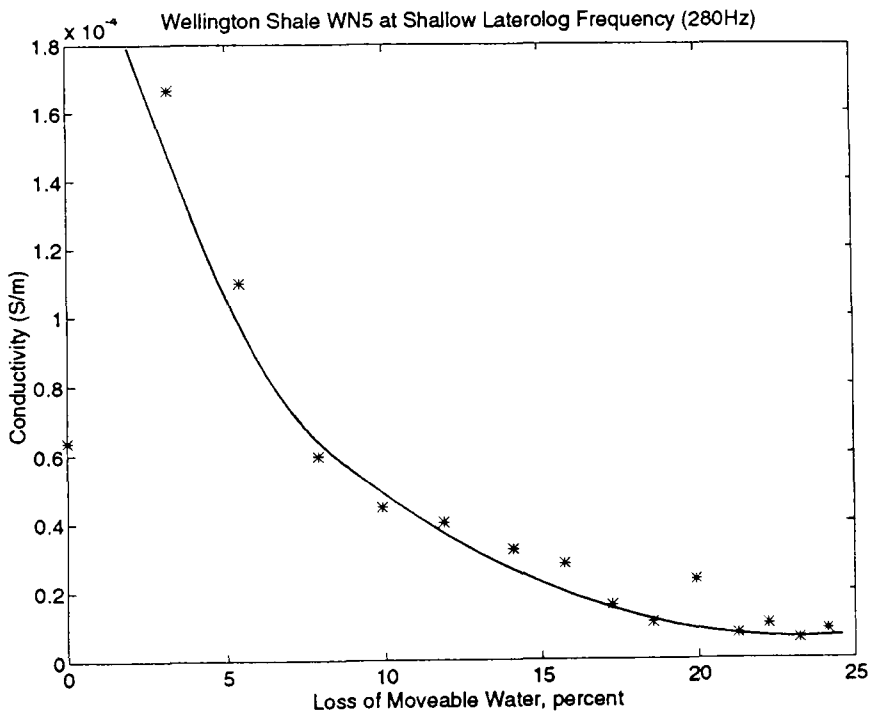

Figure A.38 Conductivity of Wellington WN5 at 280 Hz as a Function of Water Loss

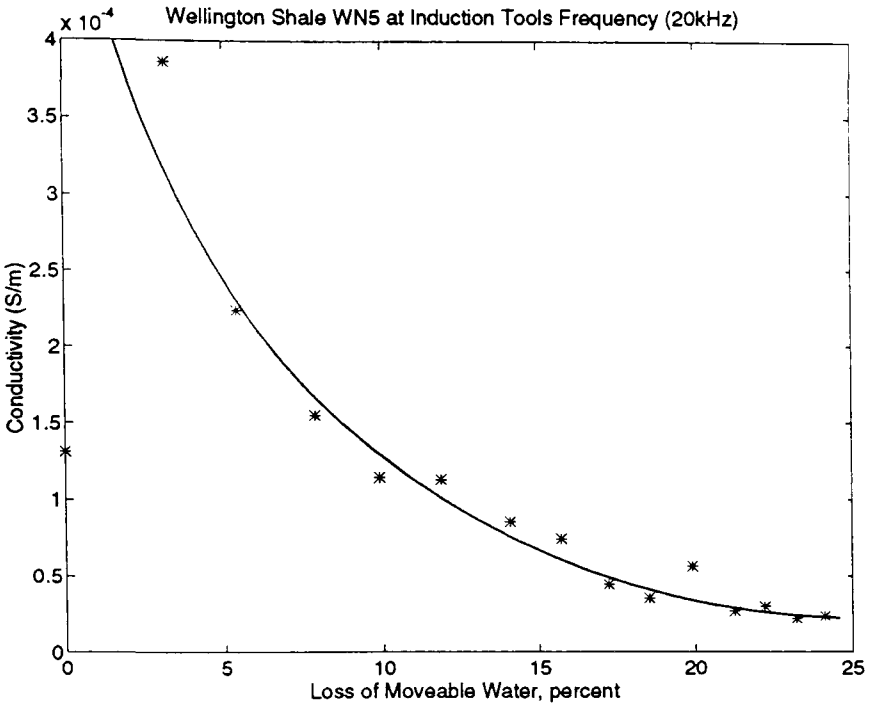

Figure A.39 Conductivity of Wellington WN5 at 20 kHz as a Function of Water Loss

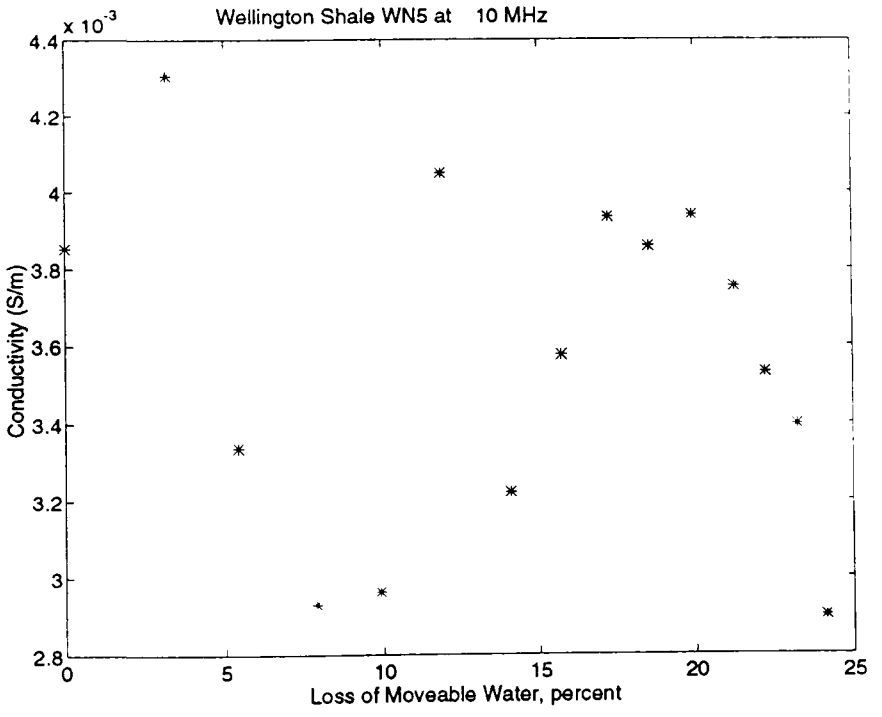

Figure A.40 Conductivity of Wellington WN5 at 10 MHz as a Function of Water Loss

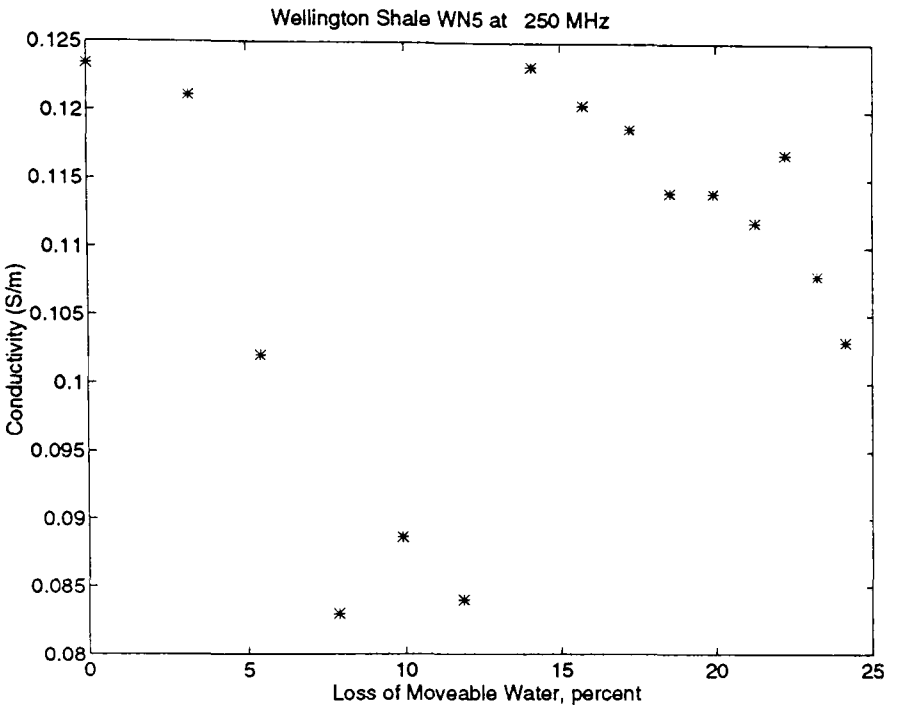

Figure A.41 Conductivity of Wellington WN5 at 250 MHz as a Function of Water Loss

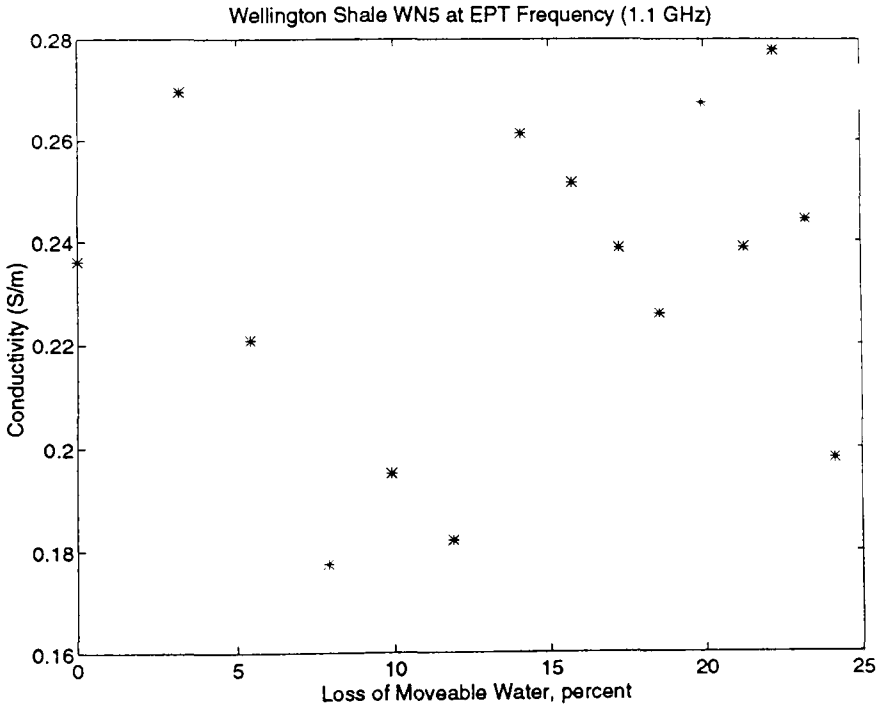

Figure A.42 Conductivity of Wellington WN5 at 1.1 GHz as a Function of Water Loss

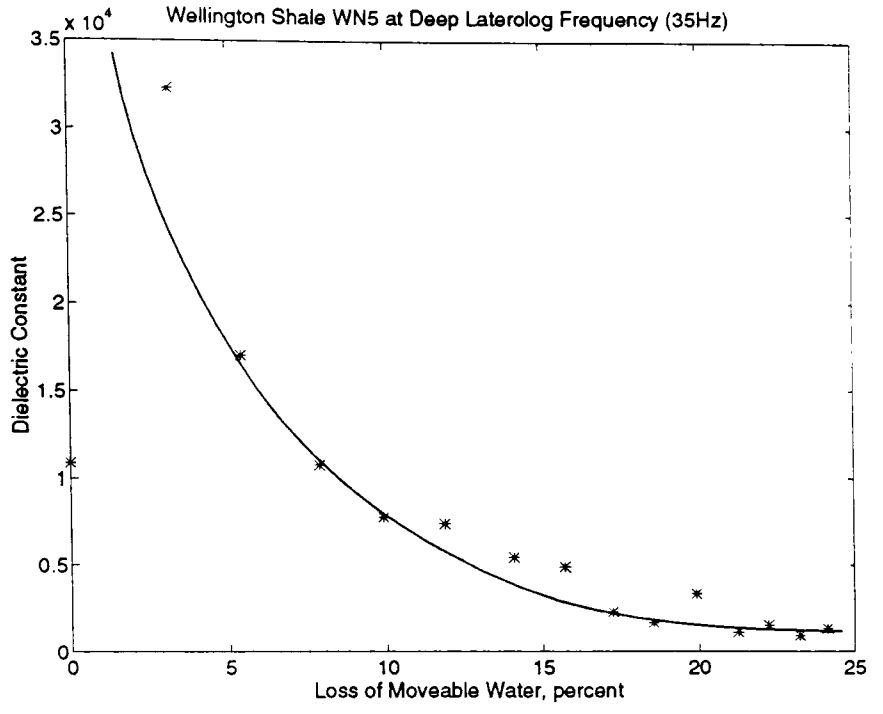

Figure A.43 Dielectric Constant of Wellington WN5 at 35 Hz as a Function of Water Loss

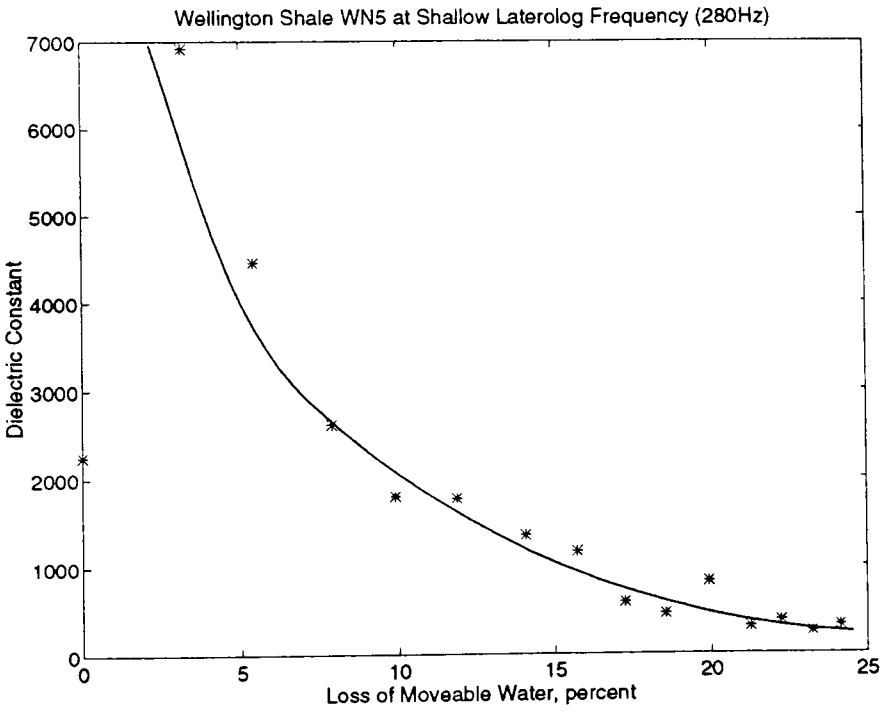

Figure A.44 Dielectric Constant of Wellington WN5 at 280 Hz as a Function of Water Loss

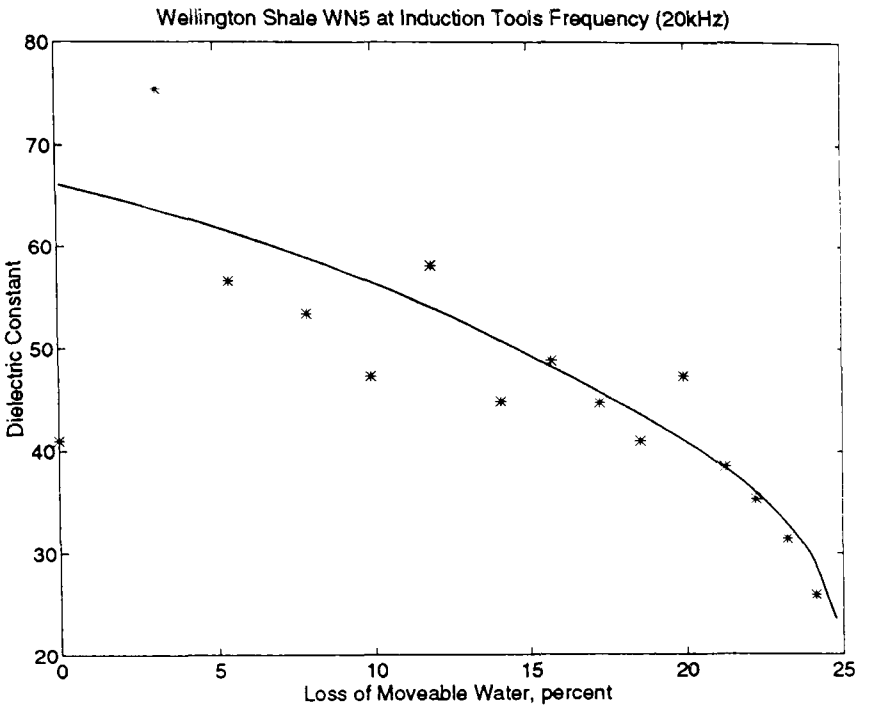

Figure A.45 Dielectric Constant of Wellington WN5 at 20 kHz as a Function of Water Loss

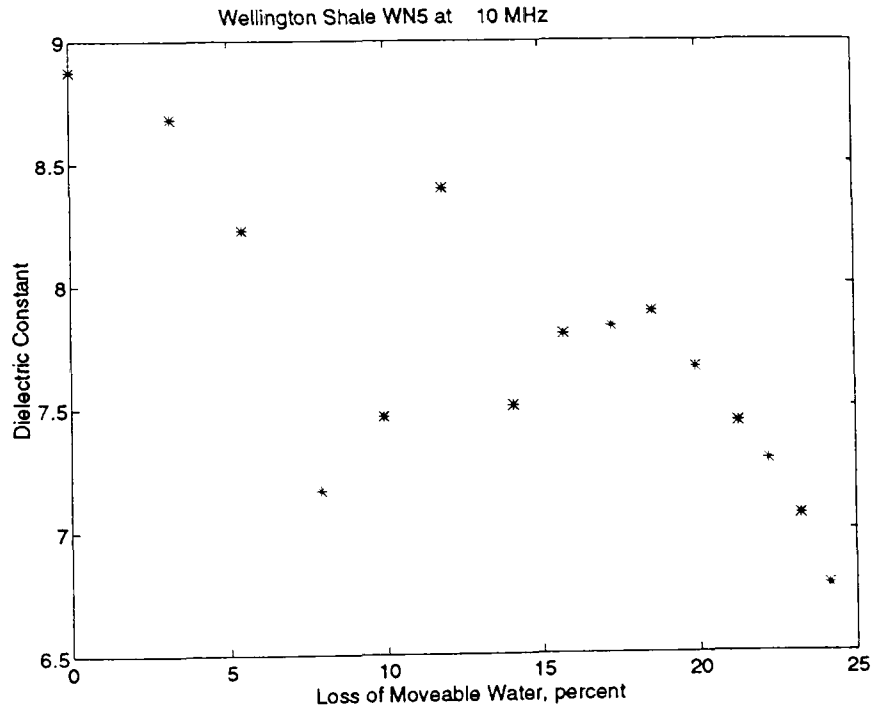

Figure A.46 Dielectric Constant of Wellington WN5 at 10 MHz as a Function of Water Loss

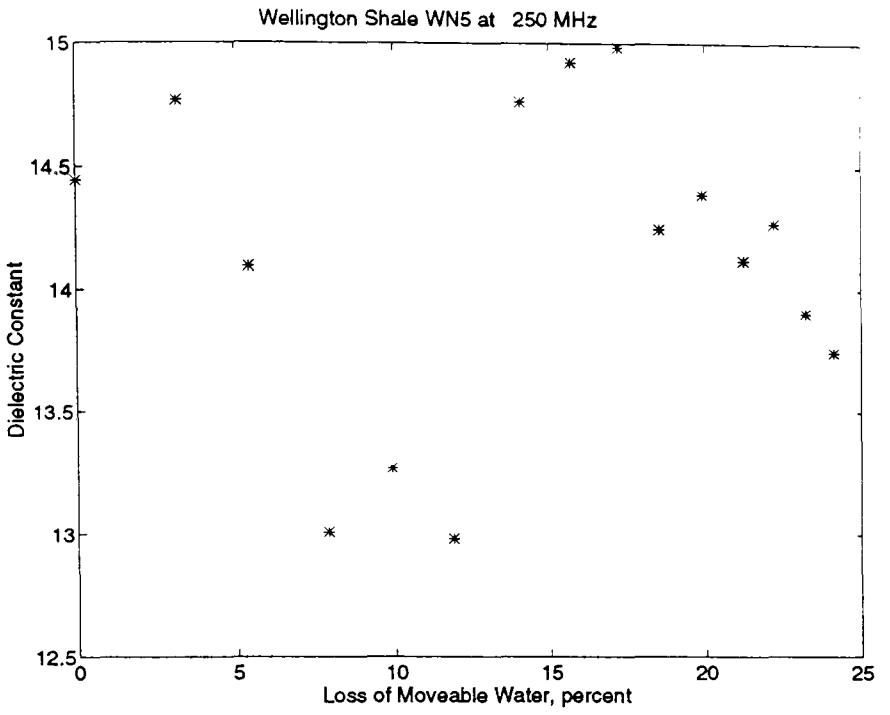

Figure A.47 Dielectric Constant of Wellington WN5 at 250 MHz as a Function of Water Loss

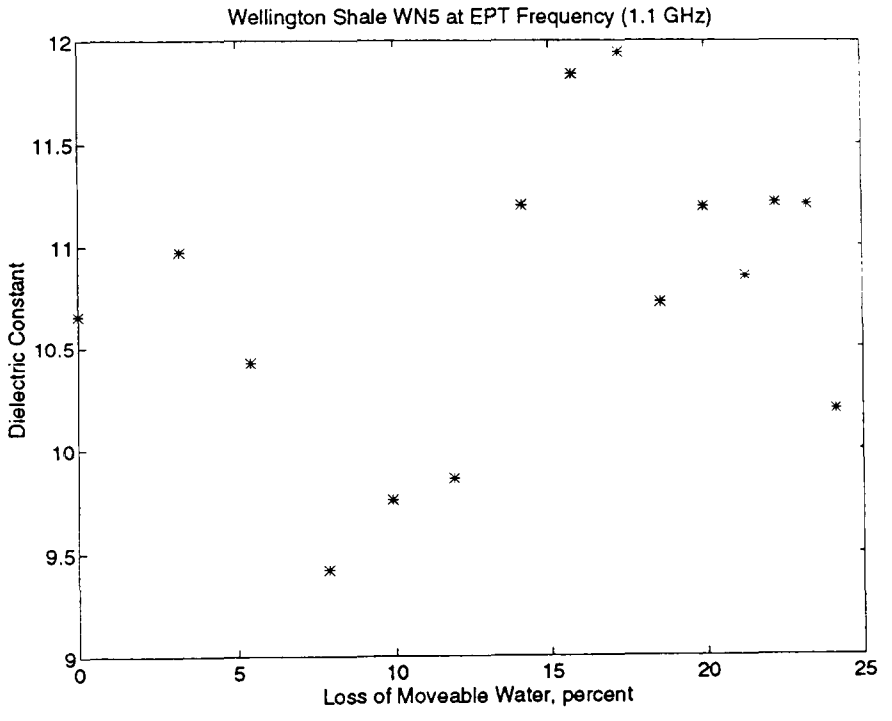

Figure A.48 Dielectric Constant of Wellington WN5 at 1.1 GHz as a Function of Water Loss

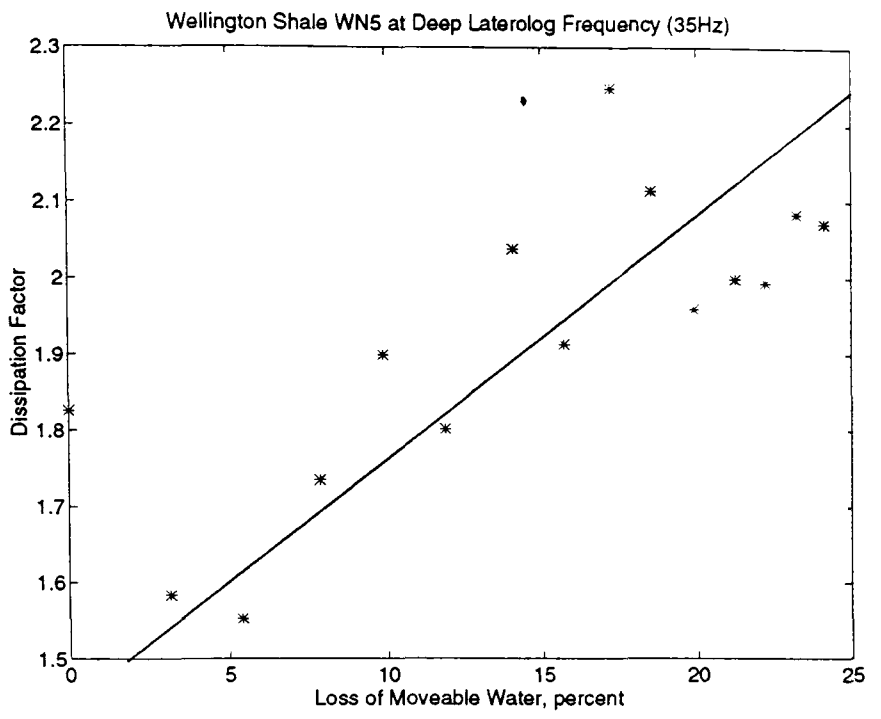

Figure A.49 Dissipation Factor of Wellington WN5 at 35 Hz as a Function of Water Loss

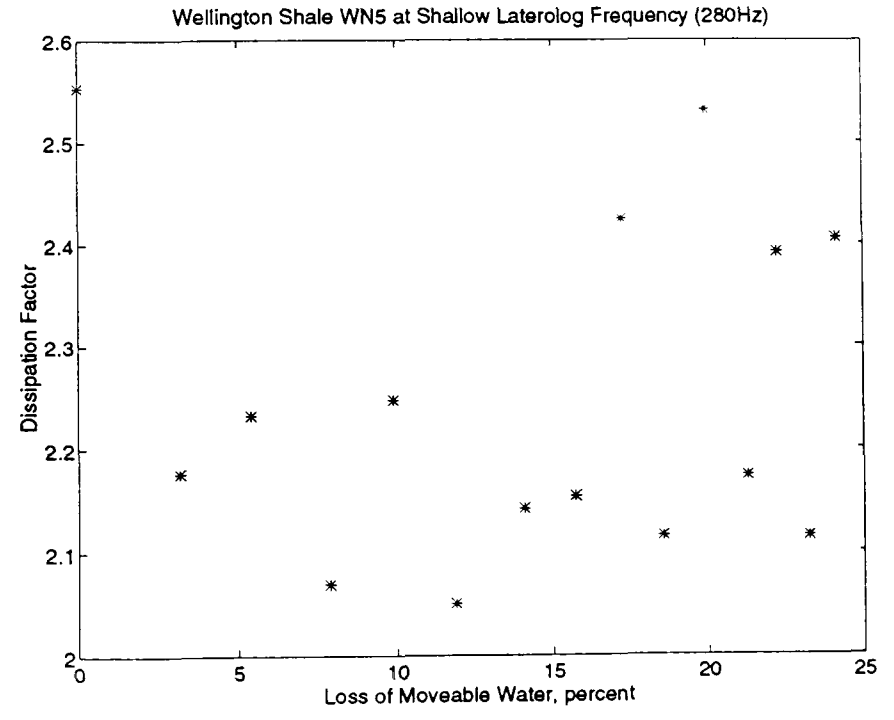

Figure A.50 Dissipation Factor of Wellington WN5 at 280 Hz as a Function of Water Loss

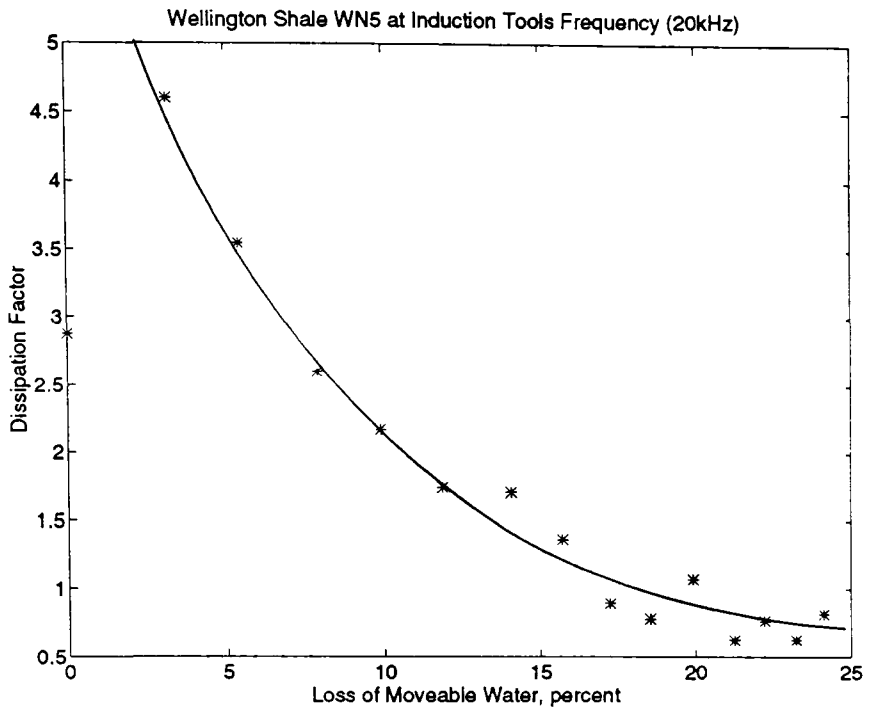

Figure A.51 Dissipation Factor of Wellington WN5 at 20 kHz as a Function of Water Loss

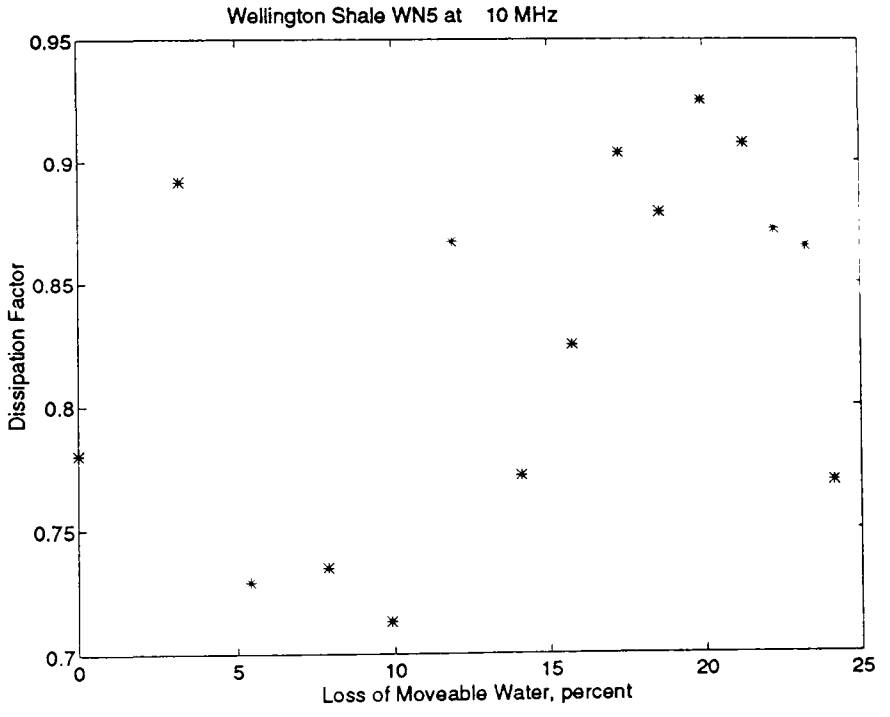

Figure A.52 Dissipation Factor of Wellington WN5 at 10 MHz as a Function of Water Loss

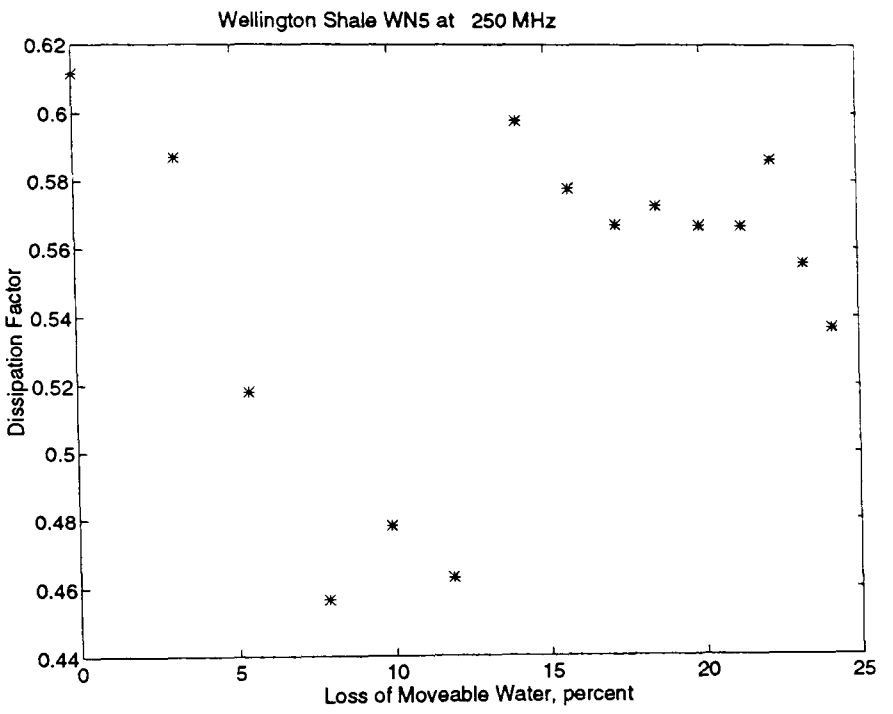

Figure A.53 Dissipation Factor of Wellington WN5 at 250 MHz as a Function of Water Loss

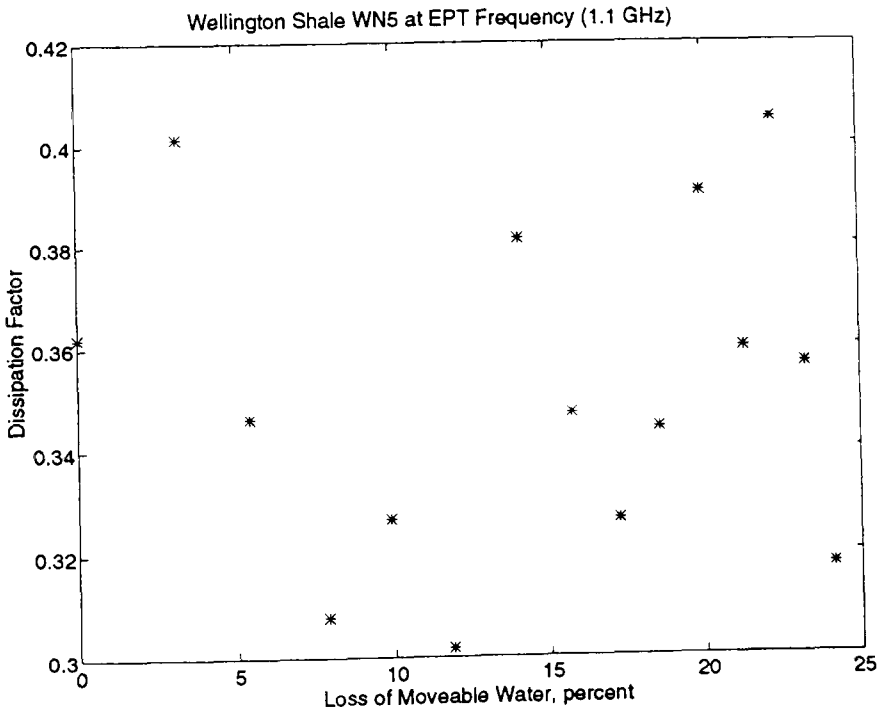

Figure A.54 Dissipation Factor of Wellington WN5 at 1.1 GHz as a Function of Water Loss

APPENDIX B

THE DATA ACQUISITION SYSTEM

Appendix B will explain, in detail, the measurement procedures used in this research. The study uses three different measurements: the low-frequency, high-frequency and acoustic-electrical measurements. To ensure a stable reading, all equipment must be on for at least 30 minutes to reach stable operating temperature.

B.1 Low Frequency Electrical Measurement

The low-frequency measurement (5 Hz up to 13 MHz) is conducted using the Hewlett-Packard 4192A Impedance Analyzer. This instrument is controlled by a micro computer thorough the IEEE-488/HPIB (Hewlett-Packard Interface Bus). The controlling software is a custom QuickBasic program that will control the analyzer to measure R, X, G and B at each frequency of interest, and will write the output as an ASCII file that can be post-processed on various spreadsheet programs or data-plotting programs.

B.1.1 Instructions for Setting Up the Equipment

The setup uses a custom sample fixture, which is basically a *4-terminal pair* setup with a coaxial cable (RG-58U) length of 104 cm. One end of the cable has BNC connectors for attaching the Impedance Analyzer, and the other end has gold palladium coated brass mesh screen to contact the sample. Figure B.1 shows the schematic of the measurement setup.

B.1.2 Instructions for Using the Program

The HP4192A Impedance Analyzer is controlled by a custom QuickBasic program. The source code is IMP.BAS and the precompiled executable is IMPxx.EXE, where xx is the version number. The program will use a configuration file, IMP.CFG, that will define some parameter such as the analyzer's HPIB address. The format is self explanatory.

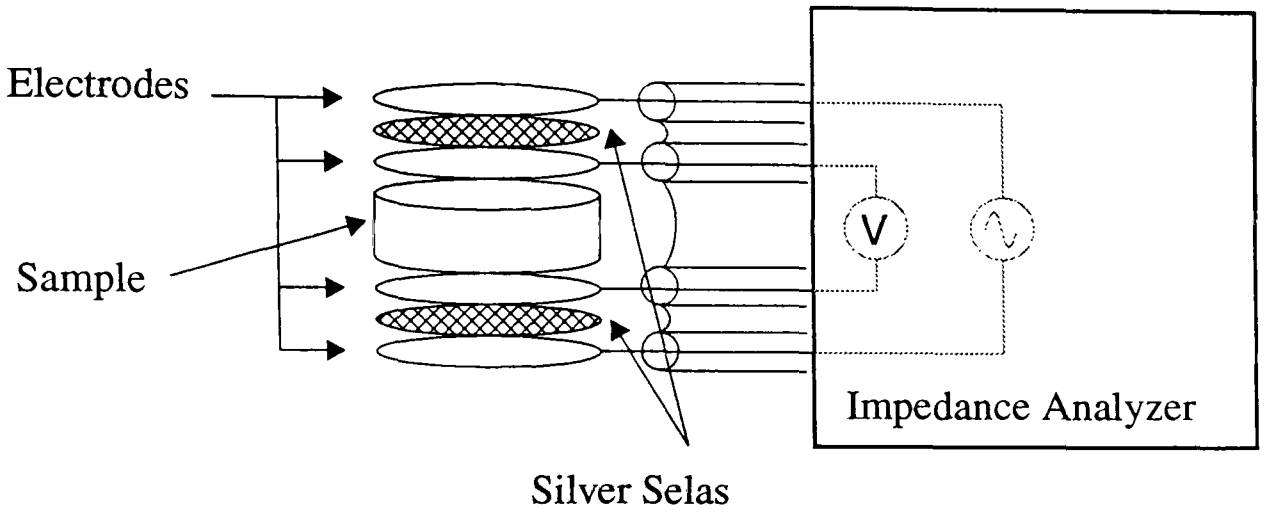

Figure B.1 Low-Frequency Measurement Setup

The next section is a typical runtime session with user response in bold face and a brief explanation enclosed in parentheses. The user must not forget to press **enter** or **return** key at the end of each line.

```
c:\> cd imp                    (go to the imp subdirectory)
c:\imp> imp53                  (start the program)
hit anykey to pass the program banner

Mode ?: 2                      (Select the acquisition mode: 1 for Known start,
                               stop and step frequencies, 2 for Spot frequency
                               mode, logarithmic increment, and 3 for batch op-
                               eration, with the frequencies defined in *.imp
                               file)
Acquired data ?: 1             (select the Z, Theta, R, X, C and D parameters
                               to acquire. Use 2 to acquire the Gain/Loss and
                               Phase measurement)
Calibration: 0                 (select no calibration, 1 for calibration before
                               the measurement)
Type of probe: 1               (select 38mm electrode, use 2 for the 5mm elec-
                               trode)

The program will then go to the file menu
Name of test sample: Pierre    (The description of the sample, can be up to 256
                               characters, but use no comma)
Thickness of sample <cm>: .8
Name of data storage file: pierre
                               (maximum 7 characters, and no extension)

If you need to edit some entry,type N and enter
or enter and anykey to start the program

The program will run, and plot G vs. frequency real-time

After the end of the measurement set, the program will accept:
    r          to repeat the same measurement
    ESC        to exit the program, back to dos
or anykey to go back to the file menu for another dataset
```

The output file is the name that the user supplies to the program, appended by a sequence number and suffixed with *.iar* (Impedance Analyzer Raw format file). This output file is in ASCII format, importable by any spreadsheet or data plotting program.

B.2 High-Frequency Electrical Measurement

The high-frequency measurement is done with an HP 8752A Network Analyzer and HP87451B Windows™-based application software. The software will control the analyzer via the HPIB bus. The analyzer will measure the reflection off of the sample and convert it, after applying the calibrations of the probe, to the real and imaginary parts of permittivity and the dissipation factor. The output is an ASCII file that can be imported to various post-processor programs such as spreadsheets or data plotting programs.

B.2.1 Instructions for Using the Program

The application software for the Network Analyzer is a commercial package that Hewlett Packard provides. The program has to run under Windows 3.1 in enhanced mode (virtual 8088 mode, not standard or real mode).

The next section is a typical runtime session with user response in bold face and a brief explanation enclosed in parentheses. The user must not forget to press **enter** or **return** key at the end of each line.

```
c:\> win                          (start Windows 3.1)
open Application group and select the HP85070A icon
select (double-click) on HP85070A icon to launch the program

hit Ok on the program banner
wait for the frequency grid to pop up

Setup, Recall Setup
select expanded.tst               (this will load the 201 datapoints from 20 MHz
                                  to 1.3 GHz. log increment setup)

go Calibration                    (start the calibration procedure)
do the open calibration
put the shorting block and do the short calibration
                                  (note: reinsert the shorting block to make the
                                  cluster reading as small and left of the screen
                                  as possible)
dip the probe into deionized water and do the water calibration

Measure, Trigger measurement      (Trigger a measurement, this action can also be
                                  selected by Control-T)
Output, Save data                 (to save the current measurement to a datafile.
                                  This action can also be selected with Control-D)
```

B.3 Combined Electrical and Acoustic Measurement

The electrical and acoustic measurement setup will measure various parameters through a digital voltmeter and a digitizing oscilloscope. The digital voltmeter, input switching (multiplexer) box and oscilloscope are connected together to the controlling computer via the GPIB bus. A custom QuickBasic application has been written to control these instruments.

B.3.1 Instructions for Running the Program

The computer program has been designed to be an easy-to-run application, with the default values stored in a configuration file to reduce the number of key inputs at run time. The next section is a typical runtime session with user response in bold face and a brief explanation enclosed in parentheses. The user must not forget to press **enter** or **return** key at the end of each line.

```
c:\> cd das                    (move to DAS subdirectory, where the program is
                                located)
c:das\>das                     (Execute the program.The program will then show
                                the current configuration, if the configuration
                                is not right, then Control-Break to exit the pro-
                                gram)
enter filename: test           (Enter the filename, max 8 characters, and no
                                suffix)
save to NFS [y/n]: n           (Type 'n' for not storing to the NFS/Network
                                File System, otherwise type 'y')
Brief description: Just a test (Type a brief explanation of the experiment,
                                maximum of 255 characters and do not use comma)
Interval (in minute): 0.5      (Time interval between data saving, in minutes.
                                The acquisition cycle will go as fast as possi-
                                ble, and between the data saving period the pro-
                                gram will average the readings)
```

The program will run as shown on the screen with values acquired from the defined inputs. While the program is running, several function keys can be used to control the program, as described in the next section.

B.3.2 Key Assignments

There are several keys available while the acquisition is taking place. Those keys are **F1** for accessing the help screen (currently unavailable), **F2** for pause (for example, to do a small adjustment on the sample without having to stop the program), **F3** to give a mark on the output file for an interesting event, and **F10** to stop and exit the program properly.

The user exits the program with F10, as this function allows the program to properly to close all output files and also to give the proper shutdown instructions to the instruments.

B.3.3 The Configuration File

The configuration file for the DAS.EXE program is called DAS.CFG, an ASCII file in the same directory as the executable. This file is not free-format, but uses either one explanation line followed by one parameter, or one explanation line followed by several parameter lines. One typical configuration file is as follows:

```
' Configuration file for DAS.BAS
' format is 'explanation line' followed by the parameter value
Version
2
LocalPath

NetPath
g:\print\
DM5120%          - Voltmeter GPIB address, and flag (-1 = enable)
16,-1
PFG5105%         - Function generator GPIB address
8,-1
DSA601%          - DSA 601 GPIB address
1,-0
MUX%             - Multiplexer box GPIB address
15,-1
DMMBuff          - Number of buffer in the DMM
100
DMMStoIn         - Interval between buffer storage, for DMM
10
*** Begin DSA Section ***
DSAChan%         - Number of acquired parameters from DSA
2
*** Next lines, put the explanations for each DSA channel, format is
*** Wfm#,Screen title, Measurement parameter, remark
1,"Cross","CROss?","First arrival"
1,"Ampl","MAX?","Amplitude of the first arrival"
*** Begin MUX Section ***
MuxInput%        - Number of inputs of the multiplexer
8
*** Next lines, explanations for each input to the Multiplexer box
*** input#,"Title","signal type", DMM range (V), remark, screen flag
1,"IDC","DCV",3,"Induced DC",-0
2,"Sense","ACV",30,"Reading across 11k standard resistor",0
3,"LVDT1","DCV",30,"lvdt#1 reading",-0
4,"LVDT2","DCV",30,"lvdt#2 reading",-0
5,"In-Temp","DCV",.3,"Fluid Temperature",-1
6,"Ou-Temp","DCV",.3,"Ambient Temperature",-1
7,"In-Hig","DCV",.3,"Balance Hig",-1
8,"Ou-Hig","DCV",.3,"Ambient Hig",-1
*** End of configuration file ***
```

B.3.4 Explanation of Each Parameter

The first three parameters are `Version`, to be used by the program to check the configuration file format; `LocalPath`, describing complete path of the saved file location (the user must leave empty for saving in the same directory as the executable); `NetPath`. path for network saving.

The next lines are for the instrument GPIB addresses and their usage flags (-1 means enabled and 0 means disable/ don't use). `DM5120%` is for the voltmeter; `PFG5105%` is the programmable signal generator (This equipment is not used anymore. It has been replaced by the multiplexer, but the parameter is still available for compatibility purpose with the older software version); `DSA601%` is the digitizing oscilloscope; and `MUX%` is the signal multiplexer box.

`DMMBuff` and `DMMStoIn` are two parameters for the voltmeter, the number of buffers in the DMM and the buffer storage interval time (in milliseconds). These two parameters are for the internal DMM averaging mode, but due to a bug in the voltmeter firmware that will generate spurious readings through this internal averaging mode, this mode is currently not used.

The next parameter is `DSAChan%`, which is the number of acquired parameters from the DSA 601 (Digitizing oscilloscope). This parameter will tell how many parameter lines to read. Each parameter line includes the following information separated by commas: DSA waveform number (the WFM number of the DSA), screen title (enclosed with double-quotation marks), measurement parameter using the DSA reserved words (enclosed with double-quotation marks), and a short remark (also enclosed with double-quotation marks).

The next parameter is `MuxInput%`. This is the number of inputs of the multiplexer. The multiplexer can have up to 32 inputs. The user should not input an open (unconnected) input as it might read random noise on the voltmeter and that noise will cause the voltmeter to take longer to settle and give the output, which in turn will slow down the whole measurement cycle. Each individual input is described in the next lines. The value of MuxInput must match with the number of the explanation lines.

The format of the `MuxInput` explanation line is input number, title for the input (enclosed by double quotation marks), signal type (ACV or DCV, enclosed by quotation marks), voltmeter measurement range (in Volt units, either 30, 3 or 0.3), a short remark enclosed by double-quotation marks, and the screen flag (-1 to print on screen, 0 for not to print). Those parameters are separated by commas.

APPENDIX C

DATA PROCESSING

This appendix contains various programs / scripts that have been used to acquire and post-process the data and for the final presentation.

The programs / scripts are either to be executed under QuickBASIC (version 4.5) or Matlab (at least version 4), and the details are shown on Table C.1:

Table C.1. Data Processing Programs / Scripts

Name	Function	Compiler / Interpreter	Figure
imp.bas	Program to control the HP4192 for low-frequency measurements.	QuickBASIC	Fig. C.1
ia-multi.bas	Read the output files from the low-frequency measurements and calculate the average values	QuickBASIC	Fig. C.2
na-multi.bas	Read the output files from the high-frequency measurements and calculate the average values	QuickBASIC	Fig. C.3
ianamrg3.bas	Merge the average values and the water content data in a file, to be used by wn3dplot.m script.	QuickBASIC	Fig. C.4
wn3dplot.m	Plot the datafile in 3D with frequency, water content, and the EM values as x, y, and z-axis, respectively.	Matlab	Fig. C.5
logfplot.m	Script to plot EM properties at logging tools frequencies as a function of water contents.	Matlab	Fig. C.6
das.bas	Program to acquire data from a Digital Multimeter and an Oscilloscope.	QuickBASIC	Fig. C.7
balance.bas	Program to acquire weight from a digital analytical balance thru its serial port periodically	QuickBASIC	Fig. C.8

```
' I M P . B A S
'
' program to acquire data using HP4192A LF Impedance Analyzer
' using QuickBASIC 4.5 and HPIB controller
' Compile with the gpib.qlb run-time library for GPIB support.
'
' Created by : Paulus S. Adisoemarta (yono@parokinet.org)
'
' Created       : October 20, 1991
' Last Modified : November 13, 1991
'                 December 19, 1991
'                 December 30, 1991
'                 March    25, 1992
'                 Look the list below
'
' added
'       check whether data is still inside recommended capacitance range
'       use automatic circuit mode, instead of forcing in series mode
'
' revision 1 (Complete Version : 3.1), June 5, 1992
'       automatic circuit mode turned off
'       add dissipation plot
'
' revision 2, July 1, 1992
'       add new plot without clearing the previous one,
'       with different colors
'
' revision 3, July 29, 1992
'       Wide-band mode, from 5 Hz to 13 MHz
'       Zero calibration is not turned off after calibration
'       Better acquisition speed
'       Better error handling scheme
'
' Version 4, August 10, 1992
'       Adding editing in sample information screen
'       Analyzer reset now is an option (so analyzer won't be reset
'       whenever this program start to run)
'
' Revision 1, September 5, 1992
'       add function to read Gain/Loss (A-B) and phase
'       without other impedance reading.
'       This function is invoked by the last parameter on the CFG file
'       Sample connection: OSC Output to end plate on the sample
'                          with GND to sense resistor (not sample plate).
'                          Chan A to 1 st probe
'                          Chan B to 2 nd probe
'
' Revision 2, September 6, 1992
'       Modify the connection from the sample to A and B terminal
'       Chan A (Reference) to sample plate (near sense resistor)
'       Chan B (test input) to 4 th probe (nearest to sense resistor)
'
' Revision 3, September 15, 1992
'       Put the Gain-Loss and Phase mode as an option on the menu
'       also add a calibration procedure which is basically
'       read the amplitude reduction and phase shift from the sense
'       resistor itself.
'
' Revision 6, May 4, 1993
'       Fix the smart subprogram that check for analyzer reading,
'       try just 3 times, after that just skip, and set flag
'       on the output as Flag 9 (on the output file)
'
' Revision 7, Jan 31, 1994
'       Add G (Conductance) and B (Susceptance) to the output file
'
' Revision 8, August 26, 1994
'       Add log-log PlotMode in G
'
```

Figure C.1 Program Listing of IMP.BAS

```
' Version 5, Revision 0, September 6, 1994
'       Add option to defined aquired parameters (ZT or RX or GB or CD)
'         on the configuration file
'       Move the configuration file on c:\config
'       Do the averaging real time, by using temporary files for storing
'          data between aquisitions and put the averaged values on the
'          final data file
'       Check filename before opening the datafile (to avoid overwriting it)
'
' Revision 1, September 22, 1994
'       Add Alcryn line on plot screen whenever string 'Alcryn' is found
'       on the sample name
'       Not done yet, Sep 29, 1994
'
' Revision 2, September 29, 1994
'       Plot G if sample not Alcryn, plot B otherwise
'
' REvision 3, October 6, 1994
'    internal 5 acquisition averaging
'    check againts file name duplication
'
DECLARE SUB IoTell (Analzr&, Tell$)
DECLARE SUB DrawBox (LfCol!, RtCol!, UpRow!, BtRow!, BoxColor!)
DECLARE SUB ReadBatch (File$, Op$, Samp$, Thc!, Diam!, ProbeDiam!, Mode!, NumSet!, Nfrq!(), PauseTime!(),
                       OutFile$(), Freqset!())
DECLARE SUB WaitForSRQ (GPIBcard&, Analzr&, SrqMode, ErrorBit)
DECLARE SUB CheckDataValid (PrevData!, NuData!, ErrorBit!)
DECLARE SUB DissPlot (Freq!, Diss!, OldFreq!, OldDiss!, Idx!, ColorNum!, Mode!)
DECLARE FUNCTION Val2Str$ (Num!)
DECLARE FUNCTION Log2Cart! (LogVal!)
DECLARE FUNCTION calibration! (Staf!, Stof!, Incf!)
'
DECLARE SUB GetHeaderValue (Header$, Param$, NumVal!)
DECLARE SUB StdDev (SumSQR!, Sum!, TotFile!, Sdev!)
DECLARE SUB LineParse (InLine$, Freq!, E1!, E2!)

'------------- HPIB Housecleaning Process --------------------
REM $INCLUDE: 'qbsetup.bas'
     'call the QuickBasic initializationfile QBSETUP - the setup program for
     'MS-DOS HP-IB Command library

OPTION BASE 1               ' Set the array base to 1 so array element numbering
                  ' begins with 1 instead of 0.
CLS                         ' Clear the computer CRT

' Read configuration file from disk, if any, if not use default

     GPIBcard& = 2      ' Assign the interface select code to a variable
                  ' This code is set on the HPIB interface card
     Analzr& = 219      ' Set the Signal Source variable to 719
                  ' (source address=19)

    'ON ERROR GOTO NoCFGfile
    CfgFile$ = "c:\config\imp.cfg"
    OPEN "imp.log" FOR OUTPUT AS #7          ' log file
    PRINT #7, " ": PRINT #7, " I M P . L O G"
    PRINT #7, " Logfile for IMP.EXE"
    PRINT #7, " ": PRINT #7, " System started on : "; DATE$; " at "; TIME$

    OPEN CfgFile$ FOR INPUT AS #1           ' system configuration file
    Header = 1: XtraPrm = 0
     WHILE Header                       ' skip the header section
        INPUT #1, a$
        IF a$ = "<Start>" THEN Header = 0     ' end of header section
     WEND
     INPUT #1, Inf            ' HPIB interface card address
     INPUT #1, Iad            ' Impedance analyzer address
     INPUT #1, WideBand       ' wide-band mode flag (1 = on)
     INPUT #1, PlotMode       ' PlotMode mode (1=Diss, 2=Gain/Phase, 3=G)
     LINE INPUT #1, AcqMode$ ' Parameters to Acquire
```

Figure C.1 Program Listing of IMP.BAS (Continued)

```
    CLOSE #1
     IF Inf > 0 AND Inf < 9 THEN GPIBcard& = Inf
     Analzr& = Inf * 100
     IF Iad > 0 AND Iad < 20 THEN Analzr& = Analzr& + Iad

     PRINT #7, " HPIB controller and Analyzer address : "; Analzr&
     PRINT #7, " Frequency Span : (0=normal, 1=wideband) "; WideBand
     PRINT #7, " Acquired parameters : "; AcqMode$
     PRINT #7, " Plot mode : "; PlotMode

NoCFGfile:                      'Skip if no configuration file

CALL IORESET(GPIBcard&)         'Set the interface to its default configuration
TIMEOUT! = 1
CALL IOTIMEOUT(GPIBcard&, TIMEOUT!)    ' Define a system timeout of 10 seconds
IF PCIB.ERR <> NOERR THEN ERROR PCIB.BASERR      ' Perform error trapping
CALL IOEOI(Analzr&, 0)          ' Disable End or Identify mode of transferring
                    ' data and perform error trapping

'-------- Check Operation, Look Whether Any Trouble With HPIB --------------
     Select$ = "A1A2A4B3C2F1D1V0H0"   ' Mode of instrument, see manual
                                                    ' Change C2 to C1 for Auto Circuit
     Tell$ = Select$ + "EX"           '  make the whole command
     CALL IoTell(Analzr&, Tell$)      '  and tell to do that
     SpotF = 250                     ' Put the intended frequency here
     SpoF$ = "FR" + Val2Str$(SpotF)   '  convert to command
     Tell$ = SpoF$ + "EX"             '  the whole command string
     CALL IoTell(Analzr&, Tell$)      '  and tell to do that
     SrqMode = 3: GOSUB IoGet         ' Get the value off the screen
     PRINT #7, " Analyzer reset, response   "; Rf; " (should be 250)"
     Rf = 250
     IF Rf <> 250 THEN
        BEEP: BEEP
        LOCATE 10, 20: PRINT "Warning, HPIB Error"
        LOCATE 12, 15: PRINT "Maybe The Impedance Analyzer is still OFF"
        WHILE INKEY$ = "": WEND: END
     END IF
'-------- Data definition stage -------------

'Declaring array for each variable that gets the value from analyzer
DIM Freq(1000), P(1000)          'Freq. read frm Analyzer, Calc. Diel. Constant
DIM X(1000), R(1000)             'X (reactance) and R (resistance)
DIM B(1000), G(1000)             'B (Susceptance) and G (Conductance)
DIM C(1000), D(1000)             'C (capacitance) and D (dissipation)
DIM Z(1000), Tet(1000)           'Z (impedance) and Tet (theta, phase angle)
DIM AB(1000)                     'Gain/Loss (A-B)
DIM Fla(1000)                    'Flag for printout result (warning if > 0)
DIM Nfrq(20), PauseTime(20)      'Number of frequency
DIM OutFile$(20), Freqset(20, 30)       'Output filename and frequency set
                                                    ' for each dataset

VerNum = 5.2       ' Version Number      <<<<<<<<<<< Important <<<<<<<<

LfCol = 20: RtCol = 64           ' Left Column and Right Column
UpRow = 3: BtRow = 16            ' Upper and Bottom Rows of a box
CALL DrawBox(LfCol, RtCol, UpRow, BtRow, BoxColor)      ' Create the text box

'----------------- MAIN SECTION --------------------------------

COLOR 7, 0
COLOR 2: LOCATE 5, 25: PRINT "WELCOME TO DIELECTRIC TEST PROGRAM"
COLOR 5: LOCATE 8, 27: PRINT "Created by : Paulus Adisoemarta"
COLOR 7: LOCATE 10, 27: PRINT "       Version #"; VerNum
COLOR 23: LOCATE 13, 29: PRINT "  Press any key to begin"
WHILE INKEY$ = "": WEND: CLS

MainLoop:                        ' Program mode selection

ModeEx = 0                              ' number to make the while loop running
```

Figure C.1 Program Listing of IMP.BAS (Continued)

```
WHILE ModeEx < 1 OR ModeEx > 3          ' loop until get the right user respond
    LfCol = 16: RtCol = 70: UpRow = 3: BtRow = 20
    CALL DrawBox(LfCol, RtCol, UpRow, BtRow, BoxColor)          ' make a nice box

    COLOR 2: LOCATE 5, 22: PRINT "Mode of Frequency"
    LOCATE 8, 23: PRINT "1 = Known Start, End, &";
    LOCATE 9, 23: PRINT "     Step Frequencies";
    LOCATE 11, 23: PRINT "2 = Spot Freq. Mode, Log Increment"
    LOCATE 13, 23: PRINT "3 = Batch Operation defined in *.IMP file"
    LOCATE 16, 23: PRINT "9 = Reset the Analyzer"
    COLOR 23: LOCATE 18, 31: INPUT "Select Mode <1-4> :"; ModeEx
    IF ModeEx < 1 OR ModeEx > 3 THEN BEEP
    IF ModeEx = 9 THEN CALL IOCLEAR(Analzr&)                ' Reset analyzer
    PRINT #7, " Mode of Operation : "; ModeEx
WEND

ModeAcq = 0                             ' number to make the while loop running
WHILE ModeAcq < 1 OR ModeAcq > 2          ' loop until get the right user respond
    LfCol = 16: RtCol = 70: UpRow = 3: BtRow = 20
    CALL DrawBox(LfCol, RtCol, UpRow, BtRow, BoxColor)          ' make a nice box

    COLOR 2: LOCATE 5, 22: PRINT "Acquired Data"
    LOCATE 8, 23: PRINT "1 = Z, Theta, R, X, C, D";
    LOCATE 10, 23: PRINT "2 = Gain/Loss and Phase"
    COLOR 23: LOCATE 14, 31: INPUT "Select Mode <1-2> :"; ModeAcq
    IF ModeAcq < 1 OR ModeAcq > 2 THEN BEEP
    PRINT #7, " Mode of Acquisition : "; ModeAcq
WEND

IF ModeEx < 4 THEN
   LfCol = 20: RtCol = 64: UpRow = 3: BtRow = 16
   CALL DrawBox(LfCol, RtCol, UpRow, BtRow, BoxColor)

   COLOR 2: LOCATE 5, 29: PRINT "Calibration Process"
   COLOR 5: LOCATE 7, 27: PRINT "0 = No calibration"
   COLOR 5: LOCATE 9, 27: PRINT "1 = Calibrate before measurement"
   COLOR 7: LOCATE 11, 27: INPUT "Select Calibration <0> "; CalSel
   PRINT #7, " Calibrate ? 0   no, 1 - yes : "; CalSel
   LfCol = 20: RtCol = 64: UpRow = 3: BtRow = 16
   CALL DrawBox(LfCol, RtCol, UpRow, BtRow, BoxColor)

   COLOR 2: LOCATE 5, 29: PRINT "Type of Probe"
   COLOR 5: LOCATE 7, 27: PRINT "1 = 38 mm diameter"
   COLOR 5: LOCATE 9, 27: PRINT "2 =  5 mm diameter"
   COLOR 7: LOCATE 11, 27: INPUT "Select Probe <1> "; ProbeType
   COLOR 23: LOCATE 13, 29: PRINT "  Press any key to begin"
   WHILE INKEY$ = "": WEND: CLS                     ' wait for a key press
   IF ProbeType = 0 THEN ProbeType = 1              ' default selection
   IF ProbeType = 1 THEN ProbeDiam = 3.8            ' Probe diameter for Diel.Const
   IF ProbeType = 2 THEN ProbeDiam = .5             ' calculation
   PRINT #7, " Probe diameter <cm> :"; ProbeDiam
END IF

' ---------------- Procedures for each mode -----------------------------

SELECT CASE ModeEx
    CASE IS = 1         '----- This input is for known increment frequency mode ----
     LfCol = 20: RtCol = 64: UpRow = 3: BtRow = 16
     CALL DrawBox(LfCol, RtCol, UpRow, BtRow, BoxColor)

     COLOR 2: LOCATE 7, 25: PRINT "Start, Stop, & Step Freq. Mode"
     COLOR 23: LOCATE 9, 25: INPUT "Start Frequency <kHz>"; Staf
     LOCATE 11, 25: INPUT "Stop Frequency <kHz>"; Stof
     LOCATE 13, 25: INPUT "Increment Frequency <kHz>"; Incf
     COLOR 2: CLS

     IF CalSel = 0 THEN GOSUB ConvertToString        ' Just convert
     IF CalSel = 1 THEN GOSUB calibration            ' do the calibration process
```

Figure C.1 Program Listing of IMP.BAS (Continued)

```
    CASE IS = 2          '--- This is for spot frequencies Log. Increment mode -------
     GOSUB CreateLogFreq
     Staf = Freq(1): Stof = Freq(Nfreq): Incf = Freq(2) - Freq(1)
     IF CalSel = 0 THEN GOSUB ConvertToString        'Just convert
     IF CalSel = 1 THEN GOSUB calibration            'do calibration

    CASE IS = 3
     LfCol = 20: RtCol = 64: UpRow = 3: BtRow = 16
     CALL DrawBox(LfCol, RtCol, UpRow, BtRow, BoxColor)
     LOCATE 5, 25: PRINT "Batch Operation Mode"
     LOCATE 7, 24: INPUT "Batch file name <.imp>"; File$

     CALL ReadBatch(File$, Op$, SampleName$, Thc, Diam, ProbeDiam, Mode, NumSet, Nfrq(), PauseTime(),
                    OutFile$(), Freqset())

     IF Mode = 2 THEN
        GOSUB CreateLogFreq
        Staf = Freq(1): Stof = Freq(Nfreq): Incf = Freq(2) - Freq(1)
     END IF
     IF Mode = 3 THEN
        Staf = Freqset(1, 1): Stof = Freqset(1, Nfrq(1)): Incf = Staf
     END IF

     CurrSet = 1: IF ProbeDiam = 0 THEN ProbeDiam = 3.8
     IF CalSel = 0 THEN GOSUB ConvertToString      'Just convert
     IF CalSel = 1 THEN GOSUB calibration          'do calibration

    CASE ELSE
     PRINT " Invalid Selection in Mode of Operation"
     WHILE INKEY$ = "": WEND: GOTO MainLoop

END SELECT

'---------------   Data Acquisition Section -----------------------

AnotherTest:
    SCREEN 0: LfCol = 20: RtCol = 70: UpRow = 5: BtRow = 22: ColorNum = 7
    CALL DrawBox(LfCol, RtCol, UpRow, BtRow, BoxColor)
    COLOR 7: LOCATE 7, 23: PRINT "Set Test Material on the HP-Electrode": COLOR 2

SrqMode = 1                              ' Flag for WaitForSRQ function

IF ModeEx < 8 THEN
    LOCATE 9, 23: PRINT "Sample Information Edit Screen"
    LOCATE 10, 23: PRINT "To retype, press <N> after the last input line"
    NotOK = -1                   ' Flag to make the while loop running
    WHILE NotOK
     LOCATE 12, 23: INPUT "Name of Test Sample       : ", SampleName$
     LOCATE 14, 23: INPUT "Thickness of Sample <cm>  : ", Thc
     LOCATE 17, 23: PRINT " 7 chars,  without extention"
     LOCATE 16, 23: INPUT "Name of Data Storage File : "; OutFl$
     LOCATE 19, 23: INPUT "Press N to retype -> ", Resp$
     IF Resp$ = "n" OR Resp$ = "N" THEN NotOK = -1 ELSE NotOK = 0
     IF OutFl$ = "" THEN NotOK = -1
     IF SampleName$ = "" THEN NotOK = -1
     IF NotOK THEN LOCATE 9, 23: PRINT "     Reenter data                    "
    WEND
    IF INSTR(LCASE$(SampleName$), "alcryn") > 0 THEN PlotMode = 4

END IF

LOCATE 19, 22: PRINT "          Press any key to begin"
LOCATE 20, 34: PRINT "Dielectric Test"
WHILE INKEY$ = "": WEND: CLS

AskAnalyzer:     ' ----------- Ask Analyzer, and get data -------------

     Nwait = 20              ' dummy var for looping in subroutine WaitForIo
     SrqMode = 1             ' flag for WaitForSRQ function
```

Figure C.1 Program Listing of IMP.BAS (Continued)

```
IF ModeEx = 1 THEN
   Tell$ = "TF" + Val2Str$(Staf) + "EX"            ' Start Freq
   CALL IoTell(Analzr&, Tell$)                     ' do it
   Tell$ = "SF" + Val2Str$(Incf) + "EX"            ' Step Freq
   CALL IoTell(Analzr&, Tell$)                     ' do it
   Tell$ = "FR" + Val2Str$(Staf) + "EX"            ' Set freq to Start Freq
   CALL IoTell(Analzr&, Tell$)                     ' do it
END IF

IF ModeEx = 3 THEN                                'wait for ModeEx = 3
    IF PauseTime(CurrSet) <> 0 THEN               'for next acquistion
     LfCol = 24: RtCol = 60: UpRow = 7: BtRow = 14
     CALL DrawBox(LfCol, RtCol, UpRow, BtRow, BoxColor)
     COLOR 7: LOCATE 10, 26: PRINT "Waiting for next acquisition set"
     CurTime = INT(TIMER)
     EnTime = PrevStTime + PauseTime(CurrSet) * 60       ' in seconds
     WHILE CurTime < EnTime
         CurTime = INT(TIMER)
         LOCATE 12, 30: PRINT "Seconds to go : "; EnTime   CurTime
         a$ = INKEY$: IF a$ <> "" THEN IF ASC(a$) = 27 THEN BEEP: STOP
     WEND
    END IF
    PrevStTime = EnTime
    IF PrevStTime = 0 THEN PrevStTime = INT(TIMER)
END IF

IF WideBand THEN
   SpotF = Freq(1)                          'put the first frequency here
   SpoF$ = "FR" + Val2Str$(SpotF)           'convert to spot freq. command
   Tell$ = SpoF$ + "EX"                     'command string
ELSE
   IF CalSel = 0 THEN Tell$ = Staf$ + Incf$ + Stof$ + "EX" ' put span
   CALL IoTell(Analzr&, Tell$)                              ' of frequency
   Select$ = "A2B2F1" + Staf$               ' recall start freq, A/B/C disp.
   Tell$ = Select$ + "W0EX"                 ' trigger at initial sweep freq.
END IF
CALL IoTell(Analzr&, Tell$)                 ' do it
K = 0: StTime$ = TIME$                      ' note start time of operation
```

```
ReadingLoop:
    K = K + 1                                       ' just a counter
    PRINT #7, "": PRINT #7, "---------------------------------------"
    Rf = Freq(K)
    PRINT #7, "Frequency : "; Rf; " kHz"            ' print this freq to log file

    IF ModeAcq = 1 THEN

     IF INSTR(AcqMode$, "ZT") > 0 THEN
     ' Z and Tet reading section (or Y and Tet in Parallel Circuit Mode)
     Tell$ = "A1B1EX"                               ' get Z and Theta mode
     PRINT #7, "    "; Tell$                        ' print to logfile
     ErrorBit = -1                                  ' Raise the flag to make
                                                                ' the following loop work
     WHILE ErrorBit                                 ' Loop to get the right data
        CALL IoTell(Analzr&, Tell$)                   ' do it
        GOSUB IoGet: Z(K) = Lf: Tet(K) = Mf: CurFreq = Rf  ' get the data
        IF NOT ErrorBit THEN                        ' For good data only
           IF K > 1 THEN                                    ' and not at 5 Hz
           CALL CheckDataValid(OldZ, Lf, ErrorBit)          ' check data validity
           ELSE                                             ' for 5 Hz only
           OldZ = Lf: OldT = Mf                             ' save the first data
           END IF
        END IF
     WEND                                           ' stop if ErrorBit=0

     IF F1$ = "YF" THEN                             ' Parallel Circuit Mode
        PRINT #7, "     -> Conversion"
        Z(K) = R(K) ^ 2 + X(K) ^ 2
     END IF
      END IF
```

Figure C.1 Program Listing of IMP.BAS (Continued)

```
 IF INSTR(AcqMode$, "RX") > 0 THEN    ' --- R and X reading section ---
Tell$ = "C2A2EX"                       ' get R and X.
PRINT #7, "    "; Tell$                ' print to logfile
ErrorBit = -1                          ' Raise the flag
WHILE ErrorBit                         ' Loop to get the right data
   CALL IoTell(Analzr&, Tell$)         '    do it
   GOSUB IoGet: R(K) = Lf: X(K) = Mf: CurFreq = Rf '  get the data
   IF NOT ErrorBit THEN                ' For good data only
      IF K > 1 THEN                          ' and not at 5 Hz
      CALL CheckDataValid(OldR, Lf, ErrorBit)   ' check data validity
      ELSE                                   ' for 5 Hz only
      OldR = Lf                           ' save the first data
      END IF
   END IF
WEND                                   ' stop if ErrorBit=0
 END IF

 IF INSTR(AcqMode$, "GB") > 0 THEN    ' --G & B reading section -----
Tell$ = "C3A2EX"                       ' Get G and B mode
PRINT #7, "    "; Tell$                ' print to logfile
ErrorBit = -1                          ' Raise the error flag
WHILE ErrorBit                         ' Loop to get the right data
   CALL IoTell(Analzr&, Tell$)         '    do it
   GOSUB IoGet: G(K) = Lf: B(K) = Mf: CurFreq = Rf  '    get the data
WEND                                   '    loop until data is right
Tell$ = "C2EX"                         ' Reset to series mode
CALL IoTell(Analzr&, Tell$)            ' do it
 END IF

 IF INSTR(AcqMode$, "CD") > 0 THEN    ' -- C and D reading section -----
Tell$ = "A4B2EX"                       ' get C and D mode
PRINT #7, "    "; Tell$                ' print to logfile
ErrorBit = -1                          ' Raise the error flag
WHILE ErrorBit                         ' Loop to get the right data
   CALL IoTell(Analzr&, Tell$)         '    do it
   GOSUB IoGet: C(K) = Lf: D(K) = Mf   '    get the data
WEND                                   '    loop until data is right
CurDissp = Mf: CurFreq = Rf            ' this step frequency and
                                                ' dissipation, for plotting
END IF

'---------------- Plot routines ----------------'

IF PlotMode = 3 THEN CurDissp = G(K)       ' Plot G instead
IF PlotMode = 4 THEN CurDissp = B(K)       ' Plot B instead
CALL DissPlot(CurFreq, CurDissp, OldFreq, OldDissp, K, ColorNum, PlotMode)
OldFreq = CurFreq: OldDissp = CurDissp  ' Save this point for next plot

IF F1$ = "CP" THEN                     ' convert frm Parallel to series
   C(K) = (1 + D(K) ^ 2) * C(K)
   PRINT #7, "     -> Conversion"
END IF

' ------------ Recommended Capacitance Range checking -------------
   Fla(K) = 0
   IF Z(K) = 0 THEN Z(K) = SQR(R(K) ^ 2 + X(K) ^ 2)     ' if no data
                                                ' for impedance, then create it
   IF C(K) = 0 THEN C(K) = 1 / (Z(K) * Rf * 6.25)       ' Create C if
                                                        ' not measured
   ImOvFr = Z(K) / Rf              ' Impedance over Frequency
                                                ' Impedance in Ohm and Freq in kHz


IF ProbeDiam = 3.8 THEN                ' For probe type A
   IF Rf < .005 THEN Fla(K) = 1        ' left side
   IF Rf > 30000 THEN Fla(K) = 5       ' right side
   IF Z(K) < 50 THEN Fla(K) = 7        ' bottom
   IF Z(K) > 1E+07 THEN Fla(K) = 3     ' upper
   IF C(K) > .0001 THEN Fla(K) = 8     ' lower left corner
   IF C(K) < 1E-12 THEN Fla(K) = 4     ' upper right corner
```

Figure C.1 Program Listing of IMP.BAS (Continued)

```
   IF ImOvFr > 1E+08 THEN Fla(K) = 2     ' upper left corner
   IF ImOvFr < .00313 THEN Fla(K) = 6    ' lower left corner
END IF

IF ProbeDiam = .5 THEN                   ' For probe type B
   IF Rf < .005 THEN Fla(K) = 1          ' left
   IF Rf > 30000 THEN Fla(K) = 5         ' right
   IF Z(K) < 100 THEN Fla(K) = 7         ' bottom
   IF Z(K) > 1E+07 THEN Fla(K) = 3       ' upper
   IF C(K) > .000005 THEN Fla(K) = 8     ' lower left corner
   IF C(K) < 1E-13 THEN Fla(K) = 4       ' upper right corner
   IF ImOvFr > 1.25E+08 THEN Fla(K) = 2 ' upper left corner
END IF

' ---------- Dielectric Constant Calculation --------------------
P(K) = Thc * C(K) * 1.438E+13            ' Diel. Constant calculation
P(K) = P(K) / ProbeDiam ^ 2              ' Diel. Constant for this probe diameter

END IF

IF ModeAcq = 2 THEN

 ' --------- Gain/Loss and Phase reading section ------------------

 Tell$ = "A5B2EXV1"                      ' get A-B and Phase mode
 PRINT #7, "    "; Tell$                 ' print to logfile
 ErrorBit = -1                           ' Raise the flag to make
                                                    ' the following loop work
 WHILE ErrorBit                          ' Loop to get the right data
    CALL IoTell(Analzr&, Tell$)             ' do it
    GOSUB IoGet: AB(K) = Lf: Tet(K) = Mf     ' get the data
    IF NOT ErrorBit THEN                 ' For good data only
       IF K > 1 THEN                             ' and not at 5 Hz
       CALL CheckDataValid(OldZ, Lf, ErrorBit)   ' check data validity
       ELSE                                      ' for 5 Hz only
       OldZ = Lf: OldT = Mf                      ' save the first data
       END IF
    END IF
 WEND                                    ' stop if ErrorBit=0
    CALL DissPlot(Rf, Lf, OldRf, OldAB, K, ColorNum, 2) ' Plot A-B point
    OldAB = Lf                                ' Save this point on the plot
    CALL DissPlot(Rf, Mf, OldRf, OldTet, K, ColorNum + 8, 2)' Plot Angle
    OldRf = Rf: OldTet = Mf                   ' Save this point

   END IF

   IF Rf >= Stof GOTO EndLoop

    SELECT CASE ModeEx          ' increment for different modes
        CASE IS = 1
         Tell$ = "W2EX": CALL IoTell(Analzr&, Tell$) 'const. inc., step up

        CASE IS = 2
         SpotF = Freq(K + 1)              'put the next frequency here
         SpoF$ = "FR" + Val2Str$(SpotF)   'convert to command
         Tell$ = SpoF$ + "EX"             'command string
         CALL IoTell(Analzr&, Tell$)      'tell to do that

        CASE IS = 3
         IF Mode = 2 THEN SpotF = Freq(K + 1)
         IF Mode = 3 THEN
            IF K = Nfrq(CurrSet) THEN GOTO EndLoop  'cease operation
            SpotF = Freqset(CurrSet, K + 1)         'next frequency
         END IF
         SpoF$ = "FR" + Val2Str$(SpotF)   ' convert to command
         Tell$ = SpoF$ + "EX"             ' command string
         CALL IoTell(Analzr&, Tell$)      ' tell to do that
        END SELECT

    GOTO ReadingLoop                  ' for another frequency
EndLoop:
TotData = K
```

Figure C.1 Program Listing of IMP.BAS (Continued)

```
' ------------------- Data saving section here ------------------------

IF ModeEx = 3 THEN P$ = OutFile$(CurrSet)

P$ = OutFl$ + LTRIM$(STR$(ColorNum)) + ".iar"    ' .IAR = Impedance Anl. Raw
OPEN P$ FOR OUTPUT AS #1
PRINT #1, "#"; UCASE$(P$)
PRINT #1, "#Data Acquired From LF Analyzer <Version"; VerNum; " > "
PRINT #1, "#Mode of operation : "; ModeEx
PRINT #1, "#Acquired parameters: "; AcqMode$
PRINT #1, "#Test Sample Name  : "; SampleName$
PRINT #1, "#Operator          : "; Op$
PRINT #1, "#Thickness <cm>    : "; Thc
PRINT #1, "#Probe Diameter,cm : "; ProbeDiam
PRINT #1, "#Total data        : "; TotData
PRINT #1, "#Time : "; TIME$; "  Date : "; DATE$

Form1$ = "+#.####^^^^"· Form2$ = ",+#.####^^^^"· Form3$ = ", ##    "

IF ModeEx = 1 OR ModeEx = 2 THEN
   PRINT #1, "# "
   IF ModeAcq = 1 THEN
      PRINT #1, "#  Freq        R          X          G          B        C       D          D
                          Dielectric       Z        Flags"
      PRINT #1, "#   Hz        (Ohm)      (Ohm)     (Siemens)  (Siemens)    F              Calculated
                          Constant       (ohms)"
   ELSE
       PRINT #1, "#  Freq       A-B        Theta"
       PRINT #1, "#   Hz         dB         deg"
   END IF
   FOR K = 1 TO TotData
       Tol = 1E-20
       IF X(K) >= Tol OR X(K) <= -Tol THEN
       Dcal = R(K) / ABS(X(K))
       ELSE
       Dcal = 9E+33
       END IF
       PRINT #1, USING Form1$; Freq(K) * 1000;          ' Note Freq in Hz !
       IF ModeEx <> 4 THEN
        PRINT #1, USING Form2$; R(K); -X(K); G(K); B(K); C(K); D(K); Dcal; P(K); Z(K);
       ELSE
        PRINT #1, USING Form2$; AB(K); Tet(K);
       END IF
       PRINT #1, USING Form3$; Fla(K)
   NEXT K
END IF

IF ModeEx = 3 THEN
   PRINT #1, "# "
   PRINT #1, "#  Freq      Dielectric  "
   PRINT #1, "#  KHz        Constant   "
   FOR K = 1 TO TotData
       PRINT #1, USING Form1$; Freq(K);
       PRINT #1, USING Form2$; P(K)
   NEXT K
END IF
CLOSE #1

'------------------- end section of program -----------------------------

IF ModeEx = 3 THEN                                  ' if ModeEx = 3 then check first
    IF CurrSet < NumSet THEN                        ' its status before quit
     CurrSet = CurrSet + 1: GOTO AskAnalyzer
    END IF
END IF

LOCATE 20, 22: PRINT "  Any key for another measurement"
LOCATE 22, 22: PRINT "Hit <r> to repeat or <esc> to exit"

SOUND 500, 5: a$ = "": WHILE a$ = "": a$ = INKEY$: WEND
```

Figure C.1 Program Listing of IMP.BAS (Continued)

```
IF ASC(a$) = 82 OR ASC(a$) = 114 THEN
    ColorNum = ColorNum - 1
    LOCATE 20, 22: PRINT STRING$(35, " ")
    LOCATE 22, 22: PRINT STRING$(35, " ")
    GOTO AskAnalyzer
END IF
IF ASC(a$) <> 27 GOTO AnotherTest

SCREEN 0: LOCATE 17, 20: PRINT " That's all folks, see ya later !!"
SOUND 700, 4: SOUND 500, 5: SOUND 750, 4: SOUND 600, 10: CLOSE
WHILE INKEY$ = "": WEND: COLOR 7, 0: END

Averaging:
```

Figure C.1 Program Listing of IMP.BAS (Continued)

```
'       I A - M U L T I. B A S
'
DIM FlnName$(10), Junk$(25), Suf$(30)
DIM Frqs(50), R(50, 20), X(50, 20), Ds(50, 20), G(50, 20), B(50, 20)
DIM Gavg(50), Gsd(50), Bavg(50), Bsd(50), DSavg(50), DSsd(50)
DIM Ravg(50), Xavg(50)

Pi = 3.14159: Eps0 = 8.854E-12          ' Constants

Fin$ = COMMAND$
'Fin$ = "alc913f7.iar"
IF Fin$ = "" THEN
   SOUND 300, 5: SOUND 600, 3: CLS : ShowProg = 1
   PRINT "                    I A   M U L T I. B A S"
   PRINT " "
   PRINT " Program to calculate better result from Impedance Analyzer"
   PRINT "      using several acquisitions to average the result"
   PRINT " Give the input filename is on the command tail"
   PRINT "      last character of filenames are defined in list file"
   WHILE INKEY$ = "": WEND: END
ELSE
   PRINT : PRINT "IA-Multi, averaging Impedance Analyzer data"
END IF

ConfDir$ = "c:\config": FlLog$ = ConfDir$ + "\ia-multi.log"
PRINT "Opening log file ("; FlLog$; ") ";
OPEN FlLog$ FOR INPUT AS #1             ' Check this file against
INPUT #1, Junk$: INPUT #1, Junk$                ' log file
A$ = LTRIM$(RTRIM$(UCASE$(Junk$)))
B$ = LTRIM$(RTRIM$(UCASE$(Fin$)))
PRINT " Done"
IF LEFT$(A$, 7) = LEFT$(B$, 7) THEN             ' Just check the first 7 chars
   PRINT "Already worked before": END            ' so quit
END IF: CLOSE

PreFn$ = UCASE$(Fin$): FlExt$ = ".udt"          ' Initial file setup
Header = 1: Count = 0                           ' Open the list file
CfgFile$ = ConfDir$ + "\ia-multi.lst"
PRINT "Open the configuration file (" + CfgFile$ + ") ";
OPEN CfgFile$ FOR INPUT AS #1
    WHILE NOT EOF(1)
       IF Header THEN                                ' For the header section
          INPUT #1, A$
          IF INSTR(A$, "extention") THEN
             FlExt$ = MID$(A$, INSTR(A$, "."), 4)       ' Grab the filename extention
          END IF
          IF INSTR(A$, "Start") > 0 THEN : Header = 0
       ELSE                                           ' For the bottom section
          Count = Count + 1:  INPUT #1, Suf$(Count)
       END IF
    WEND
CLOSE #1: TotFile = Count - 1: PRINT ", Done"
FlExt$ = UCASE$(FlExt$)                 ' Make sure file extention is Ucase
IF INSTR(PreFn$, FlExt$) > 0 THEN       ' if filename is already w/ext
   DotLoc = INSTR(PreFn$, ".")          ' then extract it
   PreFn$ = LEFT$(PreFn$, DotLoc - 1)
   PreFn$ = LEFT$(PreFn$, LEN(PreFn$)   1)      ' Make sure no index#
END IF

                                                ' Create all filenames
FOR I = 1 TO TotFile
    FlnName$(I) = PreFn$ + Suf$(I) + FlExt$
NEXT

'Open the Impedance Analyzer file
PRINT "Open the input files:  ";
FOR K = 1 TO TotFile                            ' For the whole set
    NA0Fn$ = FlnName$(K)                        ' Filename for this loop
```

Figure C.2 Program Listing of IA-MULTI.BAS

```
PRINT NA0Fn$; "  ";
IF ShowProg THEN
   LOCATE 10, 10: PRINT STRING$(20, " ")
   LOCATE 11, 10: PRINT STRING$(20, " ")
   LOCATE 12, 10: PRINT STRING$(20, " ")
   LOCATE 10, 10: PRINT "Opening file · "; NA0Fn$
END IF
Idx = 0

OPEN NA0Fn$ FOR INPUT AS #2                    ' open to read the data
FOR I = 1 TO 21                                ' Read the header
    LINE INPUT #2, Junk$(I)
    IF INSTR(Junk$(I), "Hz") > 0 THEN I = 20   ' end of header
NEXT
FileVerNum$ = MID$(Junk$(2), INSTR(Junk$(2), "Version") + 8, 3)
IF VAL(FileVerNum$) >= 5 THEN I = 7 ELSE I = 6
CALL GetHeaderValue(Junk$(I), "Thickness", Thick)    ' Get sample thickness
CALL GetHeaderValue(Junk$(I + 1), "Diameter", Diam)   ' Get probe diameter
Thick = Thick / 100!: Diam = Diam / 100!             ' Convert to meter
ConvConsts = 3.14159 * Diam ^ 2 / (4 * Thick)        ' Conversion to Ohm.Meter

NumLines = 50
IF FileVerNum$ = "3.0" THEN NumLines = 22
FOR I = 1 TO NumLines
    FileVer = VAL(FileVerNum$)
    IF FileVer >= 4.7 THEN                    ' For newer file format
        INPUT #2, Freq, R, X, G, B, C, d, Dcalc, e, Z, Fl    ' Input line
    ELSE                                      ' Older file format
        INPUT #2, Freq, R, X, C, d, Dcalc, e, Z, Fl          ' Input line
    END IF
    Idx = Idx + 1                                        ' Index
    Frqs(I) = Freq

    ' Conversion to Ohm.Meter and dissipation calculation

    R(Idx, K) = R * ConvConsts                           ' Convert to OhmM
    X(Idx, K) = X * ConvConsts                           ' Convert to OhmM
    IF Ds(Idx, K) > 1E+30 THEN Ds(Idx, K) = 0            ' For Div by Zero
    IF B < 1E-11 THEN B = 1E-11                          ' -- same --
        G(Idx, K) = G / ConvConsts                       ' g
        B(Idx, K) = B / ConvConsts                       ' b
        Ds(Idx, K) = G(Idx, K) / B(Idx, K)               ' Dissipation
        IF Freq = 1.3E+07 THEN I = 50                    ' End of loop flag
    NEXT
    TotFreq = Idx: CLOSE #2
NEXT: PRINT

'------- Mean and Standard Deviation Calculation
PRINT "Mean and Standard Deviation Calculation"
FOR J = 1 TO TotFreq
    SumR = 0: SumX = 0: SumDS = 0: SumG2 = 0: SumB2 = 0: SumDS2 = 0
    SumB = 0: SumG = 0
    FOR I = 1 TO TotFile
        SumR = SumR + R(J, I)
        SumX = SumX + X(J, I)
        SumG = SumG + G(J, I)
        SumB = SumB + B(J, I)
        SumDS = SumDS + Ds(J, I)
        SumG2 = SumG2 + G(J, I) ^ 2
        SumB2 = SumB2 + B(J, I) ^ 2
        SumDS2 = SumDS2 + Ds(J, I) ^ 2
    NEXT
    Ravg(J) = SumR / TotFile                 ' Mean of R
    Xavg(J) = SumX / TotFile                 ' Mean of X
    Gavg(J) = SumG / TotFile                 ' Mean of G
    Bavg(J) = SumB / TotFile                 ' Mean of B
    DSavg(J) = SumDS / TotFile               ' Mean of Dissipation
    CALL StdDev(SumG2, SumG, TotFile, Gsd(J))        ' Standard Deviation
    CALL StdDev(SumB2, SumB, TotFile, Bsd(J))        ' calculation
    CALL StdDev(SumDS2, SumDS, TotFile, DSsd(J))

NEXT
```

Figure C.2 Program Listing of IA-MULTI.BAS (Continued)

```
IF VAL(FileVerNum$) >= 5 THEN I = 7 ELSE I = 6
MID$(Junk$(I), INSTR(Junk$(I), ":") + 1, 1) = ","        'Insert comma
MID$(Junk$(I + 1), INSTR(Junk$(I + 1), ","), 4) = "<cm>"     'change , to <>
MID$(Junk$(I + 1), INSTR(Junk$(I + 1), ":") + 1, 1) = ","    'Insert comma

'------- Output file --------------------------
PRINT "Saving The Result To a File            "
'Fout$ = PreFn$ + ".UDT"
Fout2$ = PreFn$ + ".iat"                          ' Output file, .csv format
OPEN Fout2$ FOR OUTPUT AS #11
FOR I = 2 TO 10: PRINT #11, CHR$(34); Junk$(I); CHR$(34): NEXT
PRINT #11, CHR$(34); "# Frequency",
PRINT #11, "R avg", "X avg", "G avg", "B avg", "Diss avg", "Krel Eff", "G SD", "B SD", CHR$(34)
PRINT #11, CHR$(34); "#    Hz       (Ohm.M)      (Ohm.M)"; CHR$(34)
FOR I = 1 TO TotFreq                                    ' for the whole freqs
    EpsEff = Bavg(I) / (2 * Pi * Frqs(I) * Eps0)        ' Dielectric constant
    PRINT #11, Frqs(I); ",";                            ' freq column
   PRINT #11, Ravg(I); ","; Xavg(I); ","; Gavg(I); ","; Bavg(I); ","; DSavg(I); ","; EpsEff; ","; Gsd(I);
                        ","; Bsd(I)
NEXT
PRINT "       < < <   DONE   > > >       "

OPEN F1Log$ FOR OUTPUT AS #9                      ' Write filenames to list
    PRINT #9, "IA-Multi last processed file"
    PRINT #9, Fin$
CLOSE : END

OPEN "ia-multi.dbg" FOR OUTPUT AS #10
PRINT #10, "R"
FOR I = 1 TO TotFreq
    PRINT #10, Frqs(I); ",";                          ' freq column
    FOR J = 1 TO 5: PRINT #10, Re(I, J); ","; : NEXT: PRINT #10, ""
NEXT
PRINT #10, "X"
FOR I = 1 TO TotFreq
    PRINT #10, Frqs(I); ",";                          ' freq column
    FOR J = 1 TO 5: PRINT #10, Im(I, J); ","; : NEXT: PRINT #10, ""
NEXT
PRINT #10, "Dissipation"
FOR I = 1 TO TotFreq
    PRINT #10, Frqs(I); ",";                          ' freq column
    FOR J = 1 TO 5: PRINT #10, Ds(I, J); ","; : NEXT: PRINT #10, ""
NEXT
CLOSE

END
RETURN

' >>>>>>>>>>>>>>> ----- Subroutines Section ----- <<<<<<<<<<<<<<<<<<<<
CreateLogFreq:
   N = 0: StrExp = 0
   IF WideBand THEN                                   ' 3 freqs before the loop
       StrExp = -2: N = 3                             ' and this is the freqs
       Freq(1) = .005: Freq(2) = .006: Freq(3) = .008
   END IF
   FOR M = StrExp TO 3                          ' from 1e0 to 1e3 KHz
       FOR L = 1 TO 5                           '
        SFreq = 2 * L   2
        IF L = 1 THEN SFreq = 2 * L - 1
        N = N + 1: Freq(N) = 10 ^ (M) * SFreq
       NEXT
   NEXT M
   Freq(N + 1) = 10000: Freq(N + 2) = 12000: Freq(N + 3) = 13000 ' addtl freqs
   Nfreq = N + 3                                      ' total data points
RETURN

IoGet:                                      ' Subroutine to get string data from LF
    IF K = 1 THEN FOR IJ = 1 TO 1000: NEXT                ' loop at 5 Hz
    CALL WaitForSRQ(GPIBcard&, Analzr&, SrqMode, ErrorBit) ' wait until done
```

Figure C.2 Program Listing of IA-MULTI.BAS (Continued)

```
    IF ErrorBit = 0 THEN
       Max.Length% = 43: Act.Length% = 0          ' string to accept data frm anlzr
       Reading$ = SPACE$(Max.Length%)             ' create null string
       CALL IoEnters(Analzr&, Reading$, Max.Length%, Act.Length%)
       Df$ = MID$(Reading$, 1, 1)                 ' data status
       F1$ = MID$(Reading$, 2, 2)                 ' function status (Disp A)
       F2$ = MID$(Reading$, 17, 2)                ' function status (Disp B)
       Lf$ = MID$(Reading$, 5, 11): Lf = VAL(Lf$) ' display A
       Mf$ = MID$(Reading$, 21, 11): Mf = VAL(Mf$) ' display B
       Rf$ = MID$(Reading$, 34, 11): Rf = VAL(Rf$) ' display C (Frequency)
       'IF Df$ = "O" OR Df$ = "U" THEN ErrorBit = -1: SOUND 300, 2: SOUND 525, 7
    END IF
    PRINT #7, "    "; Reading$; " - "; ErrorBit     ' print to log file
RETURN

WaitForIo:              ' Looping just to waste time, before send another
   IF Nwait = 0 THEN Nwait = 200
   FOR i = 1 TO Nwait        ' command to HPIB
      FOR J = 1 TO 100: NEXT
   NEXT: BEEP                ' wait till complete
RETURN                       ' and give a beep

ConvertToString:        ' Subroutine to convert Freqs to string
    Staf$ = "TF" + Val2Str$(Staf)
    Stof$ = "PF" + Val2Str$(Stof)
    Incf$ = "SF" + Val2Str$(Incf)
    Freq$ = Staf$ + Incf$ + Stof$
RETURN

calibration:            ' Calibration Subroutine
'
' Function to do the calibration process, using two methods
'       1. calibrate at each frequency (for WideBand mode)
'       2. calibrate using Start, Stop, and Increment Frequencies
'
GOSUB ConvertToString          ' Make strings for start, inc., stop freqs.

LfCol = 20: RtCol = 69: UpRow = 3: BtRow = 11: SrqMode = 2
CALL DrawBox(LfCol, RtCol, UpRow, BtRow, BoxColor)

COLOR 2: LOCATE 5, 32: PRINT "Performing Open Calibration"
COLOR 5: LOCATE 7, 27: PRINT "Put Attachment For Open Calibration"
COLOR 23: LOCATE 9, 25: PRINT "Press Any key to Start Open Calibration"
WHILE INKEY$ = "": WEND: CLS

IF WideBand THEN                                  ' Open Calib. at each freq
   PRINT #7, "Instrument State : "; Select$              ' write to log
   FOR L = 1 TO Nfreq
       Freq$ = "FR" + Val2Str$(Freq(L))                  ' spot freq
       Tell$ = "A2C3" + Freq$                            ' set to R/X mode, parallel
       CALL IoTell(Analzr&, Tell$)                       ' Set the frequency
       LOCATE 15, 20: PRINT "Frequency (KHz) : "; Freq(L)
       Tell$ = "ZO1EX": CALL IoTell(Analzr&, Tell$)      ' Start Open Calib
       CALL WaitForSRQ(GPIBcard&, Analzr&, SrqMode, ErrorBit)' wait until done
   NEXT
ELSE                                              ' Open calib at 12 MHz
   Tell$ = Select$ + Freq$ + "ZO1EX"                     ' The whole command, start Open Calib
   CALL IoTell(Analzr&, Tell$)                           ' do it
   CALL WaitForSRQ(GPIBcard&, Analzr&, SrqMode, ErrorBit)        ' wait until done
END IF
SOUND 300, 5: SOUND 500, 7

LfCol = 20: RtCol = 69: UpRow = 3: BtRow = 11
CALL DrawBox(LfCol, RtCol, UpRow, BtRow, BoxColor)

COLOR 2: LOCATE 5, 31: PRINT "Open Calibration Complete"
COLOR 5: LOCATE 7, 26: PRINT "Change Attachment for Short Calibration"
COLOR 23: LOCATE 9, 25:  PRINT "Press any key to Begin Short Calibration"
WHILE INKEY$ = "": WEND: CLS
```

Figure C.2 Program Listing of IA-MULTI.BAS (Continued)

```
IF WideBand THEN                                    ' Open Calib. at each freq
   PRINT #7, "Instrument State : "; Select$                ' write to log
   FOR L = 1 TO Nfreq
       Freq$ = "FR" + Val2Str$(Freq(L))                    ' spot freq
       Tell$ = "A2C2" + Freq$                              ' set to R/X mode, series
       CALL IoTell(Analzr&, Tell$)                         ' Set the frequency
       LOCATE 15, 20: PRINT "Frequency (KHz) : "; Freq(L)
       Tell$ = "ZS1EX": CALL IoTell(Analzr&, Tell$)        ' Start Short Calib
       CALL WaitForSRQ(GPIBcard&, Analzr&, SrqMode, ErrorBit) ' wait until done
   NEXT
ELSE                                                ' Open calib at 12 MHz
   Tell$ = Select$ + Freq$ + "ZS1EX"                       'Start Close Calibration
   CALL IoTell(Analzr&, Tell$)                             ' do it
   CALL WaitForSRQ(GPIBcard&, Analzr&, SrqMode, ErrorBit) ' wait until done
END IF
SOUND 300, 5: SOUND 500, 7

RETURN

SUB CheckDataValid (PrevData, NuData, ErrorBit)
' Subprogram to check data validity
' data is valid if .5*PrevData < NuData < 2*PrevData
' if data is valid ErrorBit = 0 else ErrorBit=-1
' ErrorBit is received as is, and will be changed to -1 if data is not valid
'
   IF NuData < .5 * PrevData THEN ErrorBit = -1 ' new data is too small
   IF NuData > 2 * PrevData THEN ErrorBit = -1  ' new data is too big
   ErrorBit = 0
   IF ErrorBit THEN PRINT ">>> "; PrevData, NuData
   IF ErrorBit THEN SOUND 120, 3: SOUND 220, 1  ' make a tone :-)
   IF ErrorBit = 0 THEN                         ' if not error
      PrevData = NuData                         ' save the new data as olddata
   END IF
END SUB

SUB DissPlot (Freq, Diss, OldFreq, OldDiss, Idx, ColorNum, Mode)
'
' Subprogram to plot the result on the screen real time
' Mode :        1 -> Dissipation plot
'               2 -> Gain/Loss and Phase
'               3 -> G (Eff. Conductivity)
'
    Diss = .49 * Diss

    COLOR ColorNum                              ' and use the right color
    LOCATE 20 - ColorNum, 3: PRINT USING "#"; ColorNum
    LOCATE 25, 13: PRINT USING "Current Frequency <Hz> . #.##^^^^    Value = #.####^^^^ "; Freq * 1000;
                       Diss;

    IF Idx = 1 THEN                      ' make the bounding box and start plot
     IF ColorNum = 7 THEN               ' for the first point, create the plot area
        SCREEN 9                        ' EGA resolution
        VIEW (10, 1)-(634, 334), , 6     ' Make a rectangle viewport box
        IF Mode = 1 THEN LOCATE 1, 22: PRINT "Dissipation vs Frequency Plot"
        IF Mode = 2 THEN LOCATE 1, 20: PRINT " Gain/Loss and Phase vs Frequency Plot"
        IF Mode = 3 THEN LOCATE 1, 20: PRINT " Effective Conductivity vs Frequency"
        IF Mode = 4 THEN LOCATE 1, 20: PRINT " Effective Susceptivity vs Frequency"

        LfScl = Log2Cart(Freq)       ' Find the left scale
        'LfScl = INT(LfScl)           '   make it integer
                                                    '   and redefine viewport accordingly
        IF Mode = 1 THEN UpScl = -5: BotScl = 5
        IF Mode = 2 THEN UpScl = -20: BotScl = 20
        IF Mode > 2 THEN                                ' scale for G or B
           UpScl = -1: BotScl = -8
           IF Diss <= 1E-10 THEN Diss = 1E-10           ' to avoid taking zero log
           PRINT Diss
           Diss = LOG(Diss) / LOG(10)
        END IF
        WINDOW (LfScl, UpScl)-(4, BotScl)    ' set the window mapping
```

Figure C.2 Program Listing of IA-MULTI.BAS (Continued)

```
        LOCATE 2, 3: PRINT UpScl: LOCATE 23, 3: PRINT BotScl
        IF Mode = 3 THEN                        ' Put grids
           COLOR 6
           NPeriods = UpScl - BotScl - 1        '  Number of periods
           FOR N = 1 TO NPeriods                '  Create grid
            Yc = BotScl + N
            LINE (LfScl, Yc)-(4, Yc)      '  mark the line
           NEXT
        END IF
        IF Mode = 4 THEN                                    ' Plot Alcryn line
         F1 = .1: LoB = 1.5E-08: F2 = 13000!: HiB = .0012
         B1 = LOG(LoB) / LOG(10): B2 = LOG(HiB) / LOG(10)
         LINE (Log2Cart(F1), B1)-(Log2Cart(F2), B2)
        END IF
     END IF
     PSET (Log2Cart(Freq), Diss)      ' plot the first point
    ELSE                                 ' just take a line from the previous point
     IF Mode > 2 THEN
        IF Diss <= 1E-10 THEN Diss = 1E-10          ' to avoid taking zero log
        Diss = LOG(Diss) / LOG(10)
     END IF
     LINE (Log2Cart(OldFreq), OldDiss)-(Log2Cart(Freq), Diss)    ' plot
    END IF

END SUB                                 ' That's it dude !

SUB DrawBox (LfCol, RtCol, UpRow, BtRow, BoxColor)
    IF BoxColor = 0 THEN BoxColor = 3
    CLS : COLOR BoxColor
    HorzLen = RtCol   LfCol + 1
    LOCATE UpRow, LfCol: PRINT STRING$(HorzLen, 220);
    LOCATE BtRow, LfCol: PRINT STRING$(HorzLen, 223);
    FOR Row% = UpRow + 1 TO BtRow - 1
     LOCATE Row%, LfCol: PRINT CHR$(221);
     LOCATE Row%, RtCol: PRINT CHR$(222);
    NEXT Row%

END SUB
```

```
SUB IoTell (Analzr&, Tell$)
   ' Function to tell the machine to do the command in Tell$
   Span% = LEN(Tell$)                          ' length of the command
   CALL iooutputs(Analzr&, Tell$, Span%)            ' tell that to machine
    IF PCIB.ERR <> NOERR THEN ERROR PCIB.BASERR  ' if there is an error
END SUB

FUNCTION Log2Cart (LogVal)
    ' Function to convert log value to cart screen coordinate
    Log2Cart = LOG(LogVal) / LOG(10)
END FUNCTION

SUB ReadBatch (File$, Op$, Samp$, Thc, Diam, ProbeDiam, Mode, NumSet, Nfrq(), PauseTime(), OutFile$(),
                          Freqset())

'subroutine to read batch input file

'parse filename to check extension
File$ = UCASE$(File$)
IF RIGHT$(File$, 4) <> ".IMP" THEN File$ = File$ + ".IMP"
PRINT File$

OPEN File$ FOR INPUT AS #1
INPUT #1, Ver$

Intro = 1
WHILE Intro = 1                          'skipping the introduction section
   INPUT #1, in$
   IF in$ = "STARTDATA" THEN Intro = 0   'start reading after STARTDATA statement
WEND
```

Figure C.2 Program Listing of IA-MULTI.BAS (Continued)

```
INPUT #1, Op$
INPUT #1, Samp$
INPUT #1, Thc, Diam
INPUT #1, Mode
INPUT #1, ProbeDiam
INPUT #1, NumSet
FOR i = 1 TO NumSet                          ' read the dataset
    J = 0: L = 1
    INPUT #1, PauseTime(i)
    INPUT #1, OutFile$(i)
    IF Mode = 3 THEN                         ' For mode 3 only, user defined frequencies
       WHILE L = 1
       INPUT #1, in
       IF in > 0 THEN                            ' Find a zero in the freq. list
          J = J + 1: Freqset(i, J) = in          '      not zero, save to table
       ELSE                                      ' Caught a zero, stop reading
          L = 0                                  '      the following number
       END IF
       WEND
       Nfrq(i) = J                                  ' Number of freqs in this set
       IF Nfrq(i) = 0 THEN                          ' If the next dataset is empty
       FOR K = 1 TO Nfrq(i - 1)                     '   then take from previous dataset
           Freqset(i, K) = Freqset(i - 1, K)
       NEXT K
       END IF
    END IF
NEXT
CLOSE #1
END SUB

FUNCTION Val2Str$ (Num)
   a$ = STR$(Num)           ' Convert to string from numerical value
   Ln = LEN(a$)             ' Length of the string
   Fl = 0
   Tmp$ = MID$(a$, 2, Ln - 1)  ' start at 2nd pos, avoid blank in the beginning
   IF Num < 1 THEN
     Tmp$ = "+0" + Tmp$       ' add plus sign and a zero before decimal sign
   ELSE
     Tmp$ = "+" + Tmp$        ' add plus sign only before decimal sign
   END IF
   Pn = LEN(Tmp$)             ' look for its length
   WHILE Pn < 9               ' and then pad with zeros
     IF RIGHT$(Tmp$, 1) <> "." AND Fl = 0 THEN
        IF Num >= 1 THEN Tmp$ = Tmp$ + " "
        Fl = 1
     ELSE
        Tmp$ = Tmp$ + "0"
     END IF
     Pn = LEN(Tmp$)
   WEND
   Val2Str$ = Tmp$ + "EN"     ' attach EN string, end of field designator
END FUNCTION

SUB WaitForSRQ (GPIBcard&, Analzr&, SrqMode, ErrorBit)
SHARED PCIB.ERR, PCIB.BASERR, NOERR
'
' SrqMode: 1 for data reading
'          2 for calibration process
' ErrorBit: 0 if data is right
'           -1 if error msg came from analyzer (bit 2 or higher is set)
'
ErrorBit = 0                          ' Flag that data is not right
IF SrqMode = 0 THEN SrqMode = 2       ' to avoid no selection
IF SrqMode = 1 THEN                   ' Data acquistion mode
ChkStat:
     Srq% = 1
     CALL IoStatus(GPIBcard&, Srq%, Status%)        ' Check the SRQ line
     IF PCIB.ERR <> NOERR THEN ERROR PCIB.BASERR    '   error trapping
     FOR IJ = 1 TO 1000: NEXT                       '   do nothing :-(
     IF Status% = 0 THEN GOTO ChkStat               '   no SRQ, loop back
     CALL IoSPoll(Analzr&, Response%)               ' If SRQ raised,
```

Figure C.2 Program Listing of IA-MULTI.BAS (Continued)

```
    IF PCIB.ERR <> NOERR THEN ERROR PCIB.BASERR      '   check data bit
    IF Response% = 0 THEN GOTO ChkStat               '   loop back if none
    IF Response% > 65 THEN ErrorBit = -1             ' There is an error
    IF Response% <> 65 THEN                          '   and print to log file
       PRINT #7, "     Instr. Resp. (except 0 or 65) : "; Response%
    END IF
END IF

IF SrqMode = 2 THEN                      ' for Calibration process
   Response% = 1
   WHILE Response% > 0                          ' Loop until Calib. done
      FOR IJ = 1 TO 1000: NEXT                  '   do nothing :-(
      CALL IoSPoll(Analzr&, Response%)          '   check actual machine state
   WEND
END IF

END SUB                          ' go back to main program


SUB GetHeaderValue (Header$, Param$, NumVal)
' Subroutine to get the value at the header
'
IF INSTR(Header$, Param$) > 0 THEN NumVal = VAL(MID$(Header$, INSTR(Header$, ":") + 1))
END SUB

SUB LineParse (InLine$, Freq, E1, E2)
' Subprogram to parse the InLine (input line from file *.prn
' to Freq (frequency),E1 (real part), E2 (imaginary part)

' Get the frequency part
    DotLoc = INSTR(InLine$, ".")
    RtBorder = DotLoc + INSTR(MID$(InLine$, DotLoc + 1, 15), CHR$(9))
    Freq$ = MID$(InLine$, 1, RtBorder): Freq = VAL(Freq$)

'Get the Real Part
    DotLoc = RtBorder + INSTR(MID$(InLine$, RtBorder + 2, 30), " ")
    LfBorder = RtBorder
    RtBorder = DotLoc + INSTR(MID$(InLine$, DotLoc + 1, 20), CHR$(9))
    E1$ = MID$(InLine$, LfBorder, RtBorder - LfBorder): E1 = VAL(E1$)

'Get the Imaginary Part
    DotLoc = RtBorder + INSTR(MID$(InLine$, RtBorder + 1, 30), ".")
    LfBorder = RtBorder
    RtBorder = DotLoc + INSTR(MID$(InLine$, DotLoc, 10), CHR$(9))
    E2$ = MID$(InLine$, LfBorder, RtBorder - LfBorder): E2 = VAL(E2$)

END SUB

SUB StdDev (SumSQR, Sum, TotFile, Sdev)
    SqrPar = (SumSQR - Sum * Sum / TotFile) / (TotFile - 1)
    IF SqrPar > 0 THEN
        Sdev = SQR(SqrPar)
    ELSE
        Sdev = -999
    END IF
END SUB
```

Figure C.2 Program Listing of IA-MULTI.BAS (Continued)

```
'
'       I A - M U L T I. B A S
'
DECLARE SUB GetHeaderValue (Header$, Param$, NumVal!)
DECLARE SUB StdDev (SumSQR!, Sum!, TotFile!, Sdev!)
DECLARE SUB LineParse (InLine$, Freq!, E1!, E2!)
DIM FlnName$(10), Junk$(20), Suf$(30)
DIM Frqs(50), R(50, 20), X(50, 20), Ds(50, 20), G(50, 20), B(50, 20)
DIM Gavg(50), Gsd(50), Bavg(50), Bsd(50), DSavg(50), DSsd(50)
DIM Ravg(50), Xavg(50)

Pi = 3.14159: Eps0 = 8.854E-12          ' Constants

Fin$ = COMMAND$
IF Fin$ = "" THEN
   SOUND 300, 5: SOUND 600, 3: CLS : ShowProg = 1
   PRINT "                  I A - M U L T I. B A S"
   PRINT " "
   PRINT " Program to calculate better result from Impedance Analyzer"
   PRINT "      using several acquisitions to average the result"
   PRINT " Give the input filename is on the command tail"
   PRINT "      last character of filenames are defined in list file"
   WHILE INKEY$ = "": WEND: END
ELSE
   PRINT : PRINT "IA-Multi, averaging Impedance Analyzer data"
END IF

OPEN "ia-multi.log" FOR INPUT AS #1             ' Check this file against
WHILE NOT EOF(1)                                ' the log file
    INPUT #1, Junk$                             ' Yes we've work with this
    A$ = LTRIM$(RTRIM$(UCASE$(Junk$)))
    B$ = LTRIM$(RTRIM$(UCASE$(Fin$)))
    IF A$ = B$ THEN PRINT "Already worked before": END  ' so quit
WEND: CLOSE

PreFn$ = Fin$: FlExt$ = ".udt"                  ' Initial file setup

Header = 1: Count = 0                           ' Open the list file
CfgFile$ = "ia-multi.lst"
PRINT "Open the configuration file (" + CfgFile$ + ") "
OPEN CfgFile$ FOR INPUT AS #1
    WHILE NOT EOF(1)
       IF Header THEN                                   ' For the header section
          INPUT #1, A$
          IF INSTR(A$, "extention") THEN
             FlExt$ = MID$(A$, INSTR(A$, "."), 4)       ' Grab the filename extention
          END IF
          IF INSTR(A$, "Start") > 0 THEN : Header = 0
       ELSE                                             ' For the bottom section
          Count = Count + 1:  INPUT #1, Suf$(Count)
       END IF
    WEND
CLOSE #1: TotFile = Count - 1
FlExt$ = UCASE$(FlExt$)                 ' Make sure file extention is Ucase

IF INSTR(PreFn$, FlExt$) > 0 THEN       ' if filename is already w/ext
   DotLoc = INSTR(PreFn$, ".")          ' then extract it
   PreFn$ = LEFT$(PreFn$, DotLoc - 1)
   PreFn$ = LEFT$(PreFn$, LEN(PreFn$)   1)      ' Make sure no index#
END IF

                                                ' Create all filenames
FOR i = 1 TO TotFile
    FlnName$(i) = PreFn$ + Suf$(i) + FlExt$
NEXT

'Open the Impedance Analyzer file
PRINT "Open the input files:": PRINT "    ";
FOR K = 1 TO TotFile                            ' For the whole set
    NA0Fn$ = FlnName$(K)                        ' Filename for this loop
    PRINT NA0Fn$; "   ";
```

Figure C.3 Program Listing of IA-MULTI.BAS

```
IF ShowProg THEN
   LOCATE 10, 10: PRINT STRING$(20, " ")
   LOCATE 11, 10: PRINT STRING$(20, " ")
   LOCATE 12, 10: PRINT STRING$(20, " ")
   LOCATE 10, 10: PRINT "Opening file : "; NA0Fn$
END IF
Idx = 0

OPEN NA0Fn$ FOR INPUT AS #2                    ' open to read the data
FOR i = 1 TO 20                                      ' Read the header
    LINE INPUT #2, Junk$(i)
    IF INSTR(Junk$(i), "Hz") > 0 THEN i = 20         ' end of header
NEXT
FileVerNum$ = MID$(Junk$(2), INSTR(Junk$(2), "Version") + 8, 3)
CALL GetHeaderValue(Junk$(6), "Thickness", Thick)    ' Get sample thickness
CALL GetHeaderValue(Junk$(7), "Diameter", Diam)      ' Get probe diameter
Thick = Thick / 100!: Diam = Diam / 100!             ' Convert to meter
ConvConsts = 3.14159 * Diam ^ 2 / (4 * Thick)        ' Conversion to Ohm.Meter

NumLines = 50
IF FileVerNum$ = "3.0" THEN NumLines = 22
FOR i = 1 TO NumLines
    IF FileVerNum$ = "4.7" THEN      ' For newer file format
        INPUT #2, Freq, R, X, G, B, C, D, Dcalc, e, Z, Fl    ' Input line
    ELSE                             ' Older file format
        INPUT #2, Freq, R, X, C, D, Dcalc, e, Z, Fl    ' Input line

 '---- G and B calculation ------
        Denum = R ^ 2 + X ^ 2                        ' Denominator
        G = R / Denum: B = ABS(X) / Denum            ' G & B calc
    END IF
    Idx = Idx + 1                                    ' Index
    Frqs(i) = Freq
    R(Idx, K) = R * ConvConsts                       ' Convert to OhmM
    X(Idx, K) = X * ConvConsts                       ' Convert to OhmM
    IF Ds(Idx, K) > 1E+30 THEN Ds(Idx, K) = 0        ' For Div by Zero
    G(Idx, K) = G / ConvConsts
    B(Idx, K) = B / ConvConsts
    IF Freq = 1.3E+07 THEN i = 50                    ' End of loop flag
    NEXT
    TotFreq = Idx: CLOSE #2
NEXT: PRINT

'------- Mean and Standard Deviation Calculation
PRINT "Mean and Standard Deviation Calculation"
FOR J = 1 TO TotFreq
    SumR = 0: SumX = 0: SumDS = 0: SumG2 = 0: SumB2 = 0: SumDS2 = 0
    SumB = 0: SumG = 0
    FOR i = 1 TO TotFile
        SumR = SumR + R(J, i)
        SumX = SumX + X(J, i)
        SumG = SumG + G(J, i)
        SumB = SumB + B(J, i)
        SumDS = SumDS + Ds(J, i)
        SumG2 = SumG2 + G(J, i) ^ 2
        SumB2 = SumB2 + B(J, i) ^ 2
        SumDS2 = SumDS2 + Ds(J, i) ^ 2
    NEXT
    Ravg(J) = SumR / TotFile                 ' Mean of R
    Xavg(J) = SumX / TotFile                 ' Mean of X
    Gavg(J) = SumG / TotFile                 ' Mean of G
    Bavg(J) = SumB / TotFile                 ' Mean of B
    DSavg(J) = SumDS / TotFile               ' Mean of Dissipation
    CALL StdDev(SumG2, SumG, TotFile, Gsd(J))        ' Standard Deviation
    CALL StdDev(SumB2, SumB, TotFile, Bsd(J))        ' calculation
    CALL StdDev(SumDS2, SumDS, TotFile, DSsd(J))

NEXT
```

Figure C.3 Program Listing of IA-MULTI.BAS (Continued)

```
MID$(Junk$(6), INSTR(Junk$(6), ":") + 1, 1) = ","          'Insert comma
MID$(Junk$(7), INSTR(Junk$(7), ","), 4) = "<cm>"           'change , to <>
MID$(Junk$(7), INSTR(Junk$(7), ":") + 1, 1) = ","          'Insert comma

'------- Output file -------------------------
PRINT "Saving The Result To a File             "
'Fout$ = PreFn$ + ".UDT"
Fout2$ = PreFn$ + ".iat"
'OPEN Fout$ FOR OUTPUT AS #10                              ' Output file, .csv format
OPEN Fout2$ FOR OUTPUT AS #11                              ' open the result file
'FOR I = 2 TO 10: PRINT #10, CHR$(34); Junk$(I); CHR$(34): NEXT      ' write the header
FOR i = 2 TO 10: PRINT #11, CHR$(34); Junk$(i); CHR$(34): NEXT
'PRINT #10, "# Frequency",
PRINT #11, CHR$(34); "# Frequency",
'PRINT #10, "R avg", "X avg", "G avg", "B avg", "Diss avg", "G SD", "B SD", "Diss SD"
PRINT #11, "R avg", "X avg", "G avg", "B avg", "K Eff", "Diss avg", "G SD", "B SD", "Diss SD"; CHR$(34)
'PRINT #10, "#    Hz       (OHm.M)      (Ohm.M)"
PRINT #11, CHR$(34); "#    Hz       (Ohm.M)      (Ohm.M)"; CHR$(34)
FOR i = 1 TO TotFreq                                       ' for the whole freqs
    EpsEff = Bavg(i) / (2 * Pi * Frqs(i) * Eps0)           ' Dielectric constant
    'PRINT #10, Frqs(I),                                   ' freq column
    PRINT #11, Frqs(i); ",";                               ' freq column
    'PRINT #10, Ravg(I), Xavg(I), Gavg(I), Bavg(I), DSavg(I), Gsd(I), Bsd(I), DSsd(I)
   PRINT #11, Ravg(i); ","; Xavg(i); ","; Gavg(i); ","; Bavg(i); ","; EpsEff; ","; DSavg(i); ","; Gsd(i);
                       ","; Bsd(i); ","; DSsd(i)
NEXT
PRINT "       < < <   DONE   > > >       "

OPEN "ia-multi.log" FOR APPEND AS #9                       ' Write filenames to list
FOR K = 1 TO TotFile                                       ' for all files
    PRINT #9, FlnName$(K)                                  ' Filename
NEXT
CLOSE : END

OPEN "ia-multi.dbg" FOR OUTPUT AS #10
PRINT #10, "R"
FOR i = 1 TO TotFreq
    PRINT #10, Frqs(i); ",";                               ' freq column
    FOR J = 1 TO 5: PRINT #10, Re(i, J); ","; : NEXT: PRINT #10, ""
NEXT
PRINT #10, "X"
FOR i = 1 TO TotFreq
    PRINT #10, Frqs(i); ",";                               ' freq column
    FOR J = 1 TO 5: PRINT #10, Im(i, J); ","; : NEXT: PRINT #10, ""
NEXT
PRINT #10, "Dissipation"
FOR i = 1 TO TotFreq
    PRINT #10, Frqs(i); ",";                               ' freq column
    FOR J = 1 TO 5: PRINT #10, Ds(i, J); ","; : NEXT: PRINT #10, ""
NEXT
CLOSE

END

SUB GetHeaderValue (Header$, Param$, NumVal)
' Subroutine to get the value at the header
'
IF INSTR(Header$, Param$) > 0 THEN NumVal = VAL(MID$(Header$, INSTR(Header$, ":") + 1))
END SUB

SUB LineParse (InLine$, Freq, E1, E2)
' Subprogram to parse the InLine (input line from file *.prn
' to Freq (frequency),E1 (real part), E2 (imaginary part)

' Get the frequency part
    DotLoc = INSTR(InLine$, ".")
    RtBorder = DotLoc + INSTR(MID$(InLine$, DotLoc + 1, 15), CHR$(9))
    Freq$ = MID$(InLine$, 1, RtBorder): Freq = VAL(Freq$)
```

Figure C.3 Program Listing of IA-MULTI.BAS (Continued)

```
'Get the Real Part
    DotLoc = RtBorder + INSTR(MID$(InLine$, RtBorder + 2, 30), ".")
    LfBorder = RtBorder
    RtBorder = DotLoc + INSTR(MID$(InLine$, DotLoc + 1, 20), CHR$(9))
    E1$ = MID$(InLine$, LfBorder, RtBorder - LfBorder): E1 = VAL(E1$)

'Get the Imaginary Part
    DotLoc = RtBorder + INSTR(MID$(InLine$, RtBorder + 1, 30), ".")
    LfBorder = RtBorder
    RtBorder = DotLoc + INSTR(MID$(InLine$, DotLoc, 10), CHR$(9))
    E2$ = MID$(InLine$, LfBorder, RtBorder   LfBorder): E2 = VAL(E2$)

END SUB

SUB StdDev (SumSQR, Sum, TotFile, Sdev)
    SqrPar = (SumSQR - Sum * Sum / TotFile) / (TotFile - 1)
    IF SqrPar > 0 THEN
        Sdev = SQR(SqrPar)
    ELSE
        Sdev = -999
    END IF
END SUB

' End of File
'
```

Figure C.3 Program Listing of IA-MULTI.BAS (Continued)

```
'       N A - M U L T I. B A S
'
' last update: June 18, 1997
'
DECLARE SUB LineParse (InLine$, Freq!, E1!, E2!)
DIM FlnName$(10), Junk$(20), Suf$(30)
DIM Frqs(200), Re(200, 20), Im(200, 20), Ds(200, 20)
DIM E1avg(200), E1sd(200), E2avg(200), E2sd(200), DSavg(200), DSsd(200)
Fin$ = COMMAND$
IF Fin$ = "" THEN
   SOUND 300, 5: SOUND 600, 3
   CLS : ShowProg = 1
   PRINT "                    N A - M U L T I. B A S"
   PRINT " "
   PRINT " Program to calculate better result from Network Analyzer"
   PRINT "      using several acquisitions to average the result"
   PRINT " Give the input filename is on the command tail"
   PRINT "      last character of filenames are defined in list file"
   WHILE INKEY$ = "": WEND: END
END IF

PreFn$ = Fin$

Header = 1: Count = 0                              ' Open the list file
LstFn$ = "c:\config\na-multi.lst"
PRINT "Opening list file: "; LstFn$
OPEN LstFn$ FOR INPUT AS #1
    WHILE NOT EOF(1)
       IF Header THEN                                ' For the header section
          INPUT #1, A$
          IF INSTR(A$, "Start") > 0 THEN . Header = 0
       ELSE                                          ' For the bottom section
          Count = Count + 1:
          INPUT #1, Suf$(Count)
       END IF
    WEND
CLOSE #1: TotFile = Count   1
FOR I = 1 TO TotFile
    FlnName$(I) = PreFn$ + Suf$(I) + ".PRN"
NEXT

'FOR I = 1 TO TotFile: PRINT FlnName$(I): NEXT
'WHILE INKEY$ = "": WEND: STOP

'Open the Network Analyzer file
FOR K = 1 TO TotFile                               ' For the whole set
    NA0fn$ = FlnName$(K)                           ' Filename for this loop
    PRINT NA0fn$
    IF ShowProg THEN
       LOCATE 10, 10: PRINT STRING$(20, " ")
       LOCATE 11, 10: PRINT STRING$(20, " ")
       LOCATE 12, 10: PRINT STRING$(20, " ")
       LOCATE 10, 10: PRINT "Opening file : "; NA0fn$
    END IF
    Idx = 0: GotShift = 0
    OPEN NA0fn$ FOR INPUT AS #2                    ' input for checking file format
    INPUT #2, Junk$(1): CLOSE #2
    IF INSTR(Junk$(1), "Title") > 0 THEN                ' change LF with CR LF
       ShellCommand$ = "flipm " + NA0fn$
       SHELL ShellCommand$                              ' shell command
    END IF

    OPEN NA0fn$ FOR INPUT AS #2                    ' open to read the data
    FOR I = 1 TO 20                                     ' Read the header
        LINE INPUT #2, Junk$(I)
        IF LEFT$(Junk$(I), 9) = "frequency" THEN I   20 ' end of header
    NEXT
    FOR I   1 TO 200
        INPUT #2, InLine$
```

Figure C.4 Program Listing of NA-MULTI.BAS

```
      Idx = Idx + 1                                          ' Index
      PrevE2 = E2                                      ' Save previous E2
    CALL LineParse(InLine$, Freq, E1, E2)

      ' Routine to detect the sudden change in Imaginary reading
      IF I > 2 THEN
          IF GotShift THEN
              E2 = E2 / ShiftIm
          ELSE
              IF ABS(E2   PrevE2) > 3 THEN
                  ShiftIm = E2 / PrevE2
                  E2 = E2 / ShiftIm
                  GotShift = -1
                  PRINT ShiftIm
              END IF
          END IF
      END IF

      Frqs(I) = Freq
      Diss = E2 / E1                                          ' Dissipation calc
      Re(Idx, K) = E1: Im(Idx, K) = E2: Ds(Idx, K) = Diss
      'PRINT InLine$: PRINT Freq, E1, E2: STOP
      IF Freq = 1.3E+09 THEN I = 200                          ' end of series
  NEXT
  TotFreq = Idx: CLOSE #2
NEXT

'------- Mean and Standard Deviation Calculation
IF ShowProg THEN LOCATE 10, 10: PRINT "Mean and Standard Deviation Calculation"
FOR J = 1 TO TotFreq
    SumE1 = 0: SumE2 = 0: SumDS = 0: SumE12 = 0: SumE22 = 0: SumDS2 = 0
    FOR I = 1 TO TotFile
        SumE1 = SumE1 + Re(J, I)
        SumE2 = SumE2 + Im(J, I)
        SumDS = SumDS + Ds(J, I)
        PRINT "start SumE12"
        SumE12 = SumE12 + Re(J, I) ^ 2
        PRINT "start SumE22"
        SumE22 = SumE22 + Im(J, I) ^ 2
        PRINT "start SumDS2"
        SumDS2 = SumDS2 + Ds(J, I) ^ 2
        PRINT "End Sum"

    NEXT
    E1avg(J) = SumE1 / TotFile
    E2avg(J) = SumE2 / TotFile
    DSavg(J) = SumDS / TotFile
    E1sd(J) = SQR((SumE12 - SumE1 * SumE1 / TotFile) / (TotFile   1))
    E2sd(J) = SQR((SumE22 - SumE2 * SumE2 / TotFile) / (TotFile - 1))
    DSsd(J) = SQR((SumDS2   SumDS * SumDS / TotFile) / (TotFile - 1))
NEXT

'------- Output file --------------------------
IF ShowProg THEN LOCATE 10, 10: PRINT "Saving The Result To a File          "
Fout$ = PreFn$ + ".UDT"
Fout2$ = PreFn$ + ".csv"
OPEN Fout$ FOR OUTPUT AS #10                          ' open the result file
OPEN Fout2$ FOR OUTPUT AS #11
FOR I = 2 TO 5: PRINT #10, "#"; Junk$(I): NEXT       ' write the header
FOR I = 2 TO 5: PRINT #11, Junk$(I): NEXT
PRINT #10, "# Frequency",
PRINT #11, "Frequency",
PRINT #10, "Re avg", "Im avg", "Diss avg", "Re SD", "Im SD", "Diss SD"
PRINT #11, "Re avg", "Im avg", "Diss avg", "Re SD", "Im SD", "Diss SD"
PRINT #10, "#   Hz "
PRINT #11, "#   Hz "
FOR I = 1 TO TotFreq                                   ' for the whole freqs
    PRINT #10, Frqs(I),                               ' freq column
    PRINT #11, Frqs(I); ",";                            ' freq column
    PRINT #10, E1avg(I), E2avg(I), DSavg(I), E1sd(I), E2sd(I), DSsd(I)
    PRINT #11, E1avg(I); ","; E2avg(I); ","; DSavg(I); ","; E1sd(I); ","; E2sd(I); ","; DSsd(I)
NEXT
```

Figure C.4 Program Listing of NA-MULTI.BAS (Continued)

```
IF ShowProg THEN LOCATE 10, 10: PRINT "       < < <   DONE   > > >       "
CLOSE : END

OPEN "na-multi.log" FOR OUTPUT AS #10
PRINT #10, "Real Permittivity"
FOR I = 1 TO TotFreq
    PRINT #10, Frqs(I); ",";                          ' freq column
    FOR J = 1 TO 5: PRINT #10, Re(I, J); ","; : NEXT: PRINT #10, ""
NEXT
PRINT #10, "Imaginary Permittivity"
FOR I = 1 TO TotFreq
    PRINT #10, Frqs(I); ",";                          ' freq column
    FOR J = 1 TO 5: PRINT #10, Im(I, J); ","; : NEXT: PRINT #10, ""
NEXT
PRINT #10, "Dissipation"
FOR I = 1 TO TotFreq
    PRINT #10, Frqs(I); ",";                          ' freq column
    FOR J = 1 TO 5: PRINT #10, Ds(I, J); ","; : NEXT: PRINT #10, ""
NEXT
CLOSE

END

SUB LineParse (InLine$, Freq, E1, E2)
' Subprogram to parse the InLine (input line from file *.prn
' to Freq (frequency),E1 (real part), E2 (imaginary part)

' Get the frequency part
    DotLoc = INSTR(InLine$, ".")
    RtBorder = DotLoc + INSTR(MID$(InLine$, DotLoc + 1, 15), CHR$(9))
    Freq$ = MID$(InLine$, 1, RtBorder). Freq = VAL(Freq$)

'Get the Real Part
    DotLoc = RtBorder + INSTR(MID$(InLine$, RtBorder + 2, 30), " ")
    LfBorder = RtBorder
    RtBorder = DotLoc + INSTR(MID$(InLine$, DotLoc + 1, 20), CHR$(9))
    E1$ = MID$(InLine$, LfBorder, RtBorder - LfBorder): E1 = VAL(E1$)

'Get the Imaginary Part
    DotLoc = RtBorder + INSTR(MID$(InLine$, RtBorder + 1, 30), ".")
    LfBorder = RtBorder
    RtBorder = DotLoc + INSTR(MID$(InLine$, DotLoc, 10), CHR$(9))
    E2$ = MID$(InLine$, LfBorder, RtBorder - LfBorder): E2 = VAL(E2$)

END SUB
```

Figure C.4 Program Listing of NA-MULTI.BAS (Continued)

```
'
'       IANAMRG3 . EXE
'
' program to combine IA (.iat) and NA (.udt) files
' in 3D format:
'       X-axis: sample measurement sequence (water content)
'       Y-axis: frequency (5Hz-13MHz and 20MHz-1.3GHz)
'       Z-axis: the EM value (R or X or Re or Im or G or K or Diss)
'
' Load this program from QuickBasic with /AH option for dynamically
' arrange the big EM array.
' This program is a merge from IAT-MERG.EXE and UDT-SCAN.EXE
'
' Last Update: May 1, 1998
' Paulus Adisoemarta
'
' Nomenclatures:
'       I = index for different sample set (different time / water content)
'       J = index for a certain frequency
'       K = index for EM parameter (Ga,Gr,Ka, Kr, a-> abs, r -> rel)
'       output: aaamc.dat
'               aaa = sample name
'               m   = m (merged data)
'               c   = g (cond) or k (dielectric constant)
'               v   = a (absolute) or r (relative)

' Initialization routine
DIM Fr(30, 300), CurrLn(30), InIAFn$(30), InNAFn$(30)
FreqTot = 250
DIM EM(3, 30, FreqTot): DIM Gsd(30, FreqTot)

TotPar = 6      ' total number of EM parameters
ParSym$ = "GKD"
Pi = 3.14159: Eo = 8.854E-12

SampleSet$ = "WN1"              ' The sample set name


'--------- No User Defined Parameter Below This Line -----------------------

'Output filenames creation
    SourcePath$ = "d:\research\shale\" + SampleSet$ + "\"
      DestPath$ = "c:\apps\matlab\shale\" + SampleSet$ + "\"
    Set$ = DestPath$ + SampleSet$ + "m"
    FOR K = 1 TO TotPar / 2
        OuFn$(2 * K - 1) = Set$ + MID$(ParSym$, K, 1) + "A.dat" ' absolute
        OuFn$(2 * K) = Set$ + MID$(ParSym$, K, 1) + "R.dat"     ' relative
    NEXT

' Read the input list files, for both IA and NA and store in array vars.
    LstIAFn$ = SourcePath$ + "list-iat.txt"     ' Input IA files list
    I = 0: OPEN LstIAFn$ FOR INPUT AS #1
    WHILE NOT EOF(1)
        I = I + 1: LINE INPUT #1, InIAFn$(I)
    WEND: CLOSE #1: TotFile = I

    LstNAFn$ = SourcePath$ + "\list-udt.txt"    ' Input NA file list
    I = 0: OPEN LstNAFn$ FOR INPUT AS #1
    WHILE NOT EOF(1)
        I = I + 1: INPUT #1, InNAFn$(I)
    WEND: CLOSE #1: TotNAFile = I

    IF TotFile <> TotNAFile THEN      ' Print warning if data is unequal
        PRINT "Print IA and NA files are not equal!!": END
    END IF
    PRINT "End of reading file list"
```

Figure C.5 Program Listing of IANAMRG3.BAS

```
' Read for the whole measurement set ('a' till end)
FOR I = 1 TO TotFile

    CurrFn$ = InIAFn$(I):  Header = -1          '---- IA data reading ----
    OPEN CurrFn$ FOR INPUT AS #1
    WHILE NOT EOF(1)
        WHILE Header                        ' skip the header section
            LINE INPUT #1, a$
            IF INSTR(a$, "Ohm.M") > 0 THEN Header = 0
        WEND
        J = 0
        WHILE NOT Header
            J = J + 1
            ' input line is: Freq, R,X, G,B, Diss,Krel, Gsdv, Bsd
            FOR K = 1 TO 9
                INPUT #1, Param(K)        ' K=column, J=Row (aka freq)
            NEXT
            Fr(I, J) = Param(1): EM(1, I, J) = Param(4)
            EM(3, I, J) = Param(6): EM(2, I, J) = Param(7)
            Gsd(I, J) = Param(8)
            IF Param(1) = 1.3E+07 THEN Header = -1       'EOF signature
        WEND
    WEND: CLOSE #1: TotIA = J                    ' Total IA data

    CurrFn$ = InNAFn$(I):  Header = -1          '----- NA data reading -----
    OPEN CurrFn$ FOR INPUT AS #1
    WHILE NOT EOF(1)
        WHILE Header
            LINE INPUT #1, a$
            IF INSTR(a$, "Hz") > 0 THEN Header = 0
        WEND
        WHILE NOT Header
            J = J + 1
            INPUT #1, Fr(I, J), Re, Im, G, B, D, K, ReSD, ImSD
            EM(1, I, J) = G: EM(2, I, J) = K: EM(3, I, J) = D
            Gsd(I, J) = ImSD * 2 * Pi * Fr(I, J) * Eo    ' G calc from e"
            IF Fr(I, J) = 1.3E+09 THEN Header = -1       ' EOF signature
        WEND
    WEND: CLOSE #1
    TotLines = J
NEXT: PRINT "End of Data Input Reading"

'------------------ Data Smoothing -------------------------------------

'GOTO datasaving

IF SampleSet$ = "WN4" THEN                  ' Special case for WN4
    FOR K = 1 TO 3                          ' 8th and 13th has to be intrapolated
        FOR J = 1 TO TotIA
            I = 8: EM(K, I, J) = (EM(K, I - 1, J) + EM(K, I + 2, J)) / 2
            I = 13: EM(K, I, J) = (EM(K, I - 1, J) + EM(K, I + 2, J)) / 2
        NEXT J
    NEXT K
END IF

FOR K = 1 TO 3                              ' For all parameters
    FOR J = 1 TO TotLines                           ' for all freqs
        MinVal = 1E+15
        FOR I = 1 TO TotFile                        ' for all times (water lvl)
            IF EM(K, I, J) < MinVal THEN
               IF K > 1 THEN MinVal = EM(K, I, J) ' minimum
               IF K = 1 AND EM(1, I, J) > 0 THEN MinVal = EM(K, I, J)
            END IF
        NEXT I                                                  ' reading
        FOR I = 1 TO TotFile
            EditFlag = 0
            IF K = 1 AND EM(K, I, J) - MinVal > .5 THEN EditFlag = -1
            IF K = 1 AND EM(K, I, J) < 0 THEN EditFlag = -1
            IF K = 2 AND EM(K, I, J) - MinVal > 100000! THEN EditFlag = -1
            IF K = 3 AND EM(K, I, J) - MinVal > 100000! THEN EditFlag = -1
```

Figure C.5 Program Listing of IANAMRG3.BAS (Continued)

```
            IF EditFlag THEN
                'PRINT K; " = "; EM(K, I - 1, J), EM(K, I, J), EM(K, I + 1, J), MinVal
                EM(K, I, J) = (EM(K, I - 1, J) + EM(K, I + 1, J)) / 2
            END IF
        NEXT I
NEXT J: NEXT K

'------- Write to individual output files ------------------------------

datasaving:

FOR K = 1 TO TotPar / 2          ' (sequence is "GKD" )
    PRINT "Writing "; OuFn$(2 * K - 1); " and "; OuFn$(2 * K)
    OPEN OuFn$(2 * K   1) FOR OUTPUT AS #1
    OPEN OuFn$(2 * K) FOR OUTPUT AS #2
    IF K = 1 THEN
        OuFn$ = Set$ + "gE.dat"   ' for the ErrorBar of G
        OPEN OuFn$ FOR OUTPUT AS #3
    END IF

        FOR J = 1 TO TotLines
            PRINT #1, Fr(1, J);
            PRINT #2, Fr(1, J);
            IF K = 1 THEN PRINT #3, Fr(1, J);

            FOR I = 1 TO TotFile
                PRINT #1, EM(K, I, J);
                IF K = 1 THEN PRINT #3, Gsd(I, J);
                PRINT #2, EM(K, I, J) / EM(K, 1, J);
            NEXT I
            PRINT #1, " ": PRINT #2, " "          ' to terminate one line
            IF K = 1 THEN PRINT #3, " "
        NEXT J
        CLOSE #1: CLOSE #2
        IF K = 1 THEN CLOSE #3
                                                  ' For all output files
 NEXT K
 END
 ' End of File
```

Figure C.5 Program Listing of IANAMRG3.BAS (Continued)

```
% Filename: WN3DPLOT.m
% script to plot NA data in 3D form (pctloss, freq, G or K)
% last updated: Nov 22, 1998
% Author: Paulus S. Adisoemarta (yono@parokinet.org)

sample  = [ 1 2 4 5 ];                  % Wellington sample codes
setcode = [ 'r i d g k' ];              % real, imag, diss, G and K
params  = [ 'a' 'r' ];                  % absolute and relative values


% ---- DO NOT CHANGE ANY PARAMETER AFTER THIS LINE ----------------------

ia1=1;ia2=35;na1=36;na2=236;            % index number of IA and NA files
close                                   % close the current plot window
numsam = length(sample);                % number of samples
numset = length(setcode);               % number of parameters to plot
numpar = length(params);                % modes (absolute or relative)

% numsam = 1;: numset = 1;              % uncomment for debugging purposes

%Note that frequency axis, Y-axis, is now read from the data file
% not an individual file anymore.

% Loop for all samples
for ns=1:numsam
    samplecode = ['wn' int2str(sample(ns))];
    eval(['cd ' samplecode])            % enter the sample folder
    pctloss = [samplecode 'pct' ];      % X-axis data filename
    eval(['load ' pctloss '.dat'])      % load the X-axis data from file
    xaxis = eval([pctloss]);% X-axis (the water loss in %)

% Loop to read all files of this particular sample
for nt=1:numset
    setfile = [samplecode 'm' setcode(nt)];

    % for absolute and relatif
    for np=1:numpar
    paramfile = [setfile params(np) ];
    eval(['load ' paramfile '.dat'])    % load Z-variable

% first column is frequency, thus we have to skip it
    mn = size(eval([paramfile]));       % matrix size
    ztmp = eval([paramfile]);           % save to a temp array
    zaxis = ztmp(:,2:mn(2));            % after skipping first column
    freq = ztmp(:,1);                   % for Y-axis (Frequency)

    % Surf Plot
    hold off                                        % clear graphic
    surf(xaxis,freq(ia1:ia2), zaxis(ia1:ia2,:))     % the IA freq
    hold on                                         % combine with
    surf(xaxis,freq(na1:na2), zaxis(na1:na2,:))     % the NA freq

    set(gca,'yscale','log')                         % freq axis in log
    xlabel('Moveable Water Loss, pct'), ylabel('Frequency, Hz')

    zlabel('unknown')
    if setcode(nt) == 'g'                   % z-label for conductivity
       zlabel('Conductivity, S/m')
    end
    if setcode(nt) == 'k'                   % z-label for K
       zlabel('Dielectric Constant')
       set(gca,'zscale','log')              % z-axis in log
    end
    if setcode(nt) == 'd'
       zlabel('Dissipation Factor')
    end
```

Figure C.6 Program Listing of WN3dPLOT.M

```
      % setup plot title
      if params(np) == 'a'
         param = [' Absolute Reading'];
      else
         param = [' Relative Change'];
      end
      titlestr = ['Wellington ' upper(samplecode) param];
      title(titlestr)                          % plot title

      % error bar plot
      %paramerrbar = [setfile 'e'];            % the errorbar file
      %eval(['load ' paramerrbar '.dat']);     % and load it
      %zerrb = eval([paramerrbar]);            % move to var zerrb
      %errb = zerrb(:,2:mn(2));                % skip the first column
      %errorbar(freq,zaxis(.,1),errb(:,1))
      %axis([0 1.5e9 0 0.18])
      %set(gca,'xscale','log'),set(gca,'yscale','log')
      %xlabel('Frequency (Hz)'), ylabel('Conductivity (S/m)')
      %title('WN1 - Error Bar Plot')

      destfile = ['d:\toprint\' paramfile]
      eval(['print -depsc ' destfile ])       % save to an EPS file
      %print -dps -append wn2na3d             % for multiplot in a page
   end
end

eval(['cd ..'])                          % move back up one level
end  % the all samples block

% end of file
```

Figure C.6 Program Listing of WN3dPLOT.M (Continued)

```
% Filename: LOGFPLOT.M
% Script to plot IA data at various logging frequency of G or K
% as a function of water loss
% by Paulus Adisoemarta
% Last modification: November 30, 1998
%

setnumber = [ 0 ];                      % Wellington #, or 0 for all datafiles

insttype = [ 'n' ];                     % 'i' for IA or 'n' for NA instrument

params = str2mat( 'g', 'k' );           % EM parameters to plot, must match
                                        % with the next explanation line
paramcode = str2mat('Conductivity (S/m) ', 'Dielectric Constant');

% ---------- NO USER DEFINED PARAMETER AFTER THIS LINE --------------------

if insttype == 'i'
   setcode = [ 5 9 19 33 ];             % Index for each logging freqs
   loggingname = str2mat('Deep Laterolog Frequency (35Hz)    ','Shallow Laterolog Frequency (280Hz)','-
                         Induction Tools Frequency (20kHz)  ','   10 MHz                          ');
else
   setcode = [ 122 192 ];               % index for logging tool freqs
   loggingname = str2mat('  250 MHz              ','EPT Frequency (1.1 GHz)');
end

numfiles = length(setnumber);           % number of datafiles
if setnumber == 0                       %   if all of them
   numfiles = 4;                        %   then there are 4 data files
   setnumber = [ 1 2 4 5 ];
end
numset = length(setcode);               % number of logging frequencies
numpar = length(params);                % number of EM parameters to plot

symplot = str2mat( 'b*', 'go', 'r+', 'cx');     % plot line and symbol

close                                   % close the plot window

% Loop to read all logging frequencies
for nt=1:numset

    % for all EM parameters to plot
    for np=1:numpar
      hold off                                  % release graphic handle
      % for all datafiles
      for ns=1:numfiles
        sampletitle = ['Wellington Shale'];
        samplename  = ['WN' int2str(setnumber(ns))];                % sample name
        setfile     = ['wn' int2str(setnumber(ns)) insttype];       % sample filename
        if numfiles == 1
          sampletitle = [ sampletitle ' WN' int2str(setnumber(ns))]; % Sample title name
        end
        eval(['cd ' samplename]);                   % cd to sample folder
        pctloss = [ samplename 'pct' ];             % water loss data filename
        eval(['load ' pctloss '.dat']);             % load the file into memory
        xaxis = eval([pctloss]);                    % move to X-axis

        paramfile = [setfile params(np,:) 'a'];
        eval(['load ' paramfile '.dat'])            % load variable
        zaxis= eval([paramfile]);
        if insttype == 'n'                          % if NA data, skip leftmost column
           mn = size(eval([paramfile]));            % find the size
           zaxis = zaxis(:,2:mn(2));                % new matrix w/o freq column
        end

        % Plot for a particular frequency
        if ns > 1
           hold on                                  % hold graphic for all dataset
        end
```

Figure C.7 Program Listing of LOGFPLOT.M

```
        plot(xaxis,zaxis(setcode(nt),:),symplot(ns,:))
        xlabel('Loss of Moveable Water, percent'), ylabel(paramcode(np,:))

        titlestr = [sampletitle ' at ' loggingname(nt,:)] ;
        title(titlestr)

        % to save to individual files
        destfile = ['d:\toprint\' paramfile int2str(nt)];   % filename
        eval(['print -depsc ' destfile])        % save the plot to file
        % to print multi pages in a file
        %print -dps -append multps
        eval(['cd ..'])                 % back to parent directory
      end                               % for all data files
    end
end                                     % for all logging frequencies

% end of file
```

Figure C.7 Program Listing of LOGFPLOT.M (Continued)

```
'       D A S   B A S   (Data Acquisition System)
'
' program for acquiring data from DMM and Digital Oscilloscope.
' by Paulus Adisoemarta, May 5, 1995
' basic code taken from DMM20.BAS
'
' Function key definitions
'       F1      Help (still not implemented)
'       F2      Pause (toggle on/off)
'       F3      Dump the waveform to a file
'       F10/ESC Terminate
'
'
REM $INCLUDE: 'qbdecl.bas'
'
DECLARE SUB CheckPID (Mode)
DECLARE SUB BogoMips (Mins!, BogoIndex!)
DECLARE SUB FirstArrival (Ident%, Wfm%, Mode%, Reading!)
DECLARE SUB SumAvg (Mode!, NData!, Value!, NewValue!)
DECLARE SUB UsePFG (Ident%, Txt1$, Txt2$)
DECLARE SUB UseDMM (Ident%, Mode%, DMMfun$, DMMrng, BufSize%, StoInt%, DCV)
DECLARE SUB UseDSA (Ident%, Param$, NAvg%, Trace%, Reading!)
DECLARE SUB UseMux (Ident%, Mode%, Stream%, QueryBack$)
DECLARE SUB ReportError (fd%, errmsg$)  ' Error subroutine

DIM ChnTitle$(32), DMMfun$(32), DMMrng(32), ChnRem$(32)
DIM DMMscrprn(32), DMMavg(32)

HomeTest = -1           ' Put -1 for testing at home
Version = 1.1

' Variable set-up
Quot1$ = CHR$(34)       ' Double quote
Quot2$ = "," + CHR$(34) ' comma and double quote

CALL CheckPID(1)        ' Check if another copy of this program is running
GOSUB ReadCFG           ' Read the configuration file
CLS : GOSUB PrintCFGtoScreen
PRINT "Anykey to continue, Ctrl-Break to cancel": WHILE INKEY$ = "": WEND

IF HomeTest THEN DMMenabled = 0: MUXenabled = 0: DSAenabled = 0

' Equipment initialization
IF DMMenabled THEN GOSUB PrepareDMM: CALL UseDMM(DMM%, 1, "adc", 2, 0, 0, DCV)
IF MUXenabled THEN GOSUB PrepareMux: CALL UseMux(Mux%, 1, Inpt%, Back$)
IF DSAenabled THEN GOSUB PrepareDSA


' Program Banner

CLS : PRINT "               DAS . BAS   (version:"; Version; ")"
PRINT "Data Acquisition System"
PRINT " Acquiring data from Digital Oscilloscope and Digital voltmeter"
PRINT " and control a signal input multiplexer if necessary"
PRINT
INPUT "Filename for saving the numbers "; DataFile$
INPUT "Save a file to NFS drive too ? <n/y>"; NFStoo$
INPUT "Please enter a brief explanation for this data file "; Junk$
INPUT "Time (minutes) between acquisition "; AcqInt

GOSUB OpenOutputFile

' ---------- The data acquisition loop -------------------------

StartTime = TIMER
Acquisition = -1        ' Flag to do data acquisition
NewScreen = -1  ' Flag to set to print the screen output column heading
WHILE Acquisition
     NoMeasurement = 0
```

Figure C.8 Program Listing of DAS.BAS

```
CALL CheckPID(2)              ' Update the PID file

' Keyboard control,       ESC or F10 ends this program
  a$ = INKEY$: B = 0
  IF a$ <> "" THEN                ' a key is hit
     IF LEN(a$) = 1 THEN
     IF ASC(a$) = 27 THEN Acquisition = 0
     ELSE
     B = ASC(MID$(a$, 2))
     SELECT CASE B
         CASE 59              ' F1 help screen
          GOSUB HelpScreen

         CASE 60              ' F2 is pressed, pausing the program
          IF PauseCond THEN PauseCond = 0 ELSE PauseCond = -1: PauseStart = 0

         CASE 61
          CALL FirstArrival(DSA%, CrsStream%, 3, WfmSer!)
          WfmSer = WfmSer + 1          ' Increment the file counter

         CASE 62              ' F4 one-step mode
          PRINT "One step mode / debugging is still not implemented"

         CASE 67              ' F9 print configuration screen to screen
          PRINT "Print program configuration to screen, unimplemented"

         CASE 68              ' F10 is pressed, exit
          Acquisition = 0

     END SELECT
     END IF
  END IF
  IF PauseCond THEN
     IF PauseStart + 20 < TIMER THEN
     PRINT " ---   Program Paused  --- Hit F2 to rerun": BEEP
     PauseStart = TIMER
     END IF
     NoMeasurement = -1
  END IF
```

```
  IF Acquisition = 0 THEN
      PRINT "Closing down all open files"
      CLOSE : NoMeasurement = -1
  END IF

IF NOT NoMeasurement THEN
 Mode = 1                  ' Summing up mode
 IF DSAenabled THEN        ' DSA measurements
     FOR I = 1 TO DSAinput%
      Stream% = INT(DSAchn(I))
      CALL UseDSA(DSA%, DSAmeasm$(I), NAvg%, Stream%, DSAval(I))
      CALL SumAvg(Mode, NdataDSAval(I), DSAval(I), SumDSAval(I))
     NEXT
 END IF

 IF DMMenabled THEN

     FOR I = 1 TO MuxInput%
      CALL UseMux(Mux%, 2, INT(I), QueryBack$)
      CALL UseDMM(DMM%, 3, DMMfun$(I), DMMrng(I), BS%, SI%, DMMval(I))
      CALL SumAvg(Mode, NdataDMMval(I), DMMval(I), SumDMMval(I))
     NEXT
 END IF

 'IF Resistance THEN
 '    Res = (DCPos / DCNeg) * 11000!   ' resistance calculation
 '    CALL SumAvg(Mode, NdataRes, Res, SumRes)
 'END IF

 ' For Induced DC measurement
 'IF InducedDC THEN CALL UseDMM(DMM%, Txt$, Res, NAvg%)    ' direct reading
```

Figure C.8 Program Listing of DAS.BAS (Continued)

```
' Check for saving time
IF ThisTime + AcqInt * 60 <= TIMER THEN

    ' Do the averaging
    IF NOT AcqInt = 0 THEN       ' if AcqInt=0 then NO Averaging
      Mode = 2     ' Averaging mode
      FOR I = 1 TO DSAinput%
     CALL SumAvg(Mode, NdataDSAval(I), SumDSAval(I), DSAval(I))
      NEXT
      FOR I = 1 TO MuxInput%
     CALL SumAvg(Mode, NdataDMMval(I), SumDMMval(I), DMMval(I))
      NEXT
    END IF

    Elapsed = TIMER - StartTime          ' Elapsed time (seconds)
    IF NewScreen THEN PRINT Header1$: TotScreenLines = 0: NewScreen = 0

    ' Do the acoustic travel time correction , taking out the changing
    ' travel time in the junks (isolator and electrical electrode)
    Crs2 = Crs
    'IF Load THEN Crs2 = Crs - (Y0 + Y1 * LoadVal)

    ' Calculate the first arrival from the dumped waveform
    'Stream% = 1: Mode% = 2
    'CALL FirstArrival(DSA%, Stream%, Mode%, Zero!)

    ' Print to screen
    PRINT TIME$; : PRINT USING Form1$; Elapsed;
    FOR I = 1 TO DSAinput%
     IF DSAscrprn(I) THEN PRINT USING Form3$; DSAval(I);
    NEXT
    FOR I = 1 TO MuxInput%
     IF DMMscrprn(I) THEN PRINT USING Form3$; DMMval(I);
    NEXT: PRINT

    TotScreenLines = TotScreenLines + 1 ' Number of lines on screen
    IF TotScreenLines > 15 THEN NewScreen = -1

        ' Print to output file
        OPEN File1$ FOR APPEND AS #1
        PRINT #1, USING Form2$; TIMER; Elapsed;
        FOR I = 1 TO DSAinput%: PRINT #1, USING Form4$; DSAval(I); : NEXT
        FOR I = 1 TO MuxInput%: PRINT #1, USING Form4$; DMMval(I); : NEXT
        PRINT #1, " ": CLOSE #1
        IF Network THEN
          OPEN File2$ FOR APPEND AS #2

          FOR I = 1 TO DSAinput%: PRINT #2, USING Form4$; DSAval(I); Y: NEXT
          FOR I = 1 TO MuxInput%: PRINT #2, USING Form4$; DMMval(I); Y: NEXT
          PRINT #2, " ": CLOSE #2
        END IF

        ' Timekeeping management
        ThisTime = TIMER                    ' Starting time this acq set
        IF ThisTime + AcqInt * 60 > 24 * 60! * 60 THEN ' See if it
           ThisTime = ThisTime   24 * 60! * 60          ' almost midnight
        END IF
     END IF
     'IF WfmDownload THEN CALL FirstArrival(Ident%, Stream%, Mode%, Zero!)
    END IF
WEND

'  Bring all equipment off-line
   CALL CheckPID(3)                         ' Clear the PID file
   IF Voltage THEN CALL IBONL(DMM%, 0): CALL IBONL(PFG%, 0)      ' for DMM
   IF CrossTM OR LVDT THEN CALL IBONL(DSA%, 0)                   ' for DSA
   PRINT . PRINT "End of execution, all done"
END
```

Figure C.8 Program Listing of DAS.BAS (Continued)

```
PrepareDMM:      ' -------- Digital Multimeter setting up ---------------
'  Bring the digital multimeter on-line
   CALL IBDEV(0, DM5120%, 0, T20s, 1, 0, DMM%)
   IF (DMM% < 0) THEN CALL ReportError(DMM%, "Could not open device DMM")
RETURN

PrepareMux:
'  Bring the Mux488 on-line
   CALL IBDEV(0, Mux488%, 0, T10s, 1, 0, Mux%)
   IF (Mux% < 0) THEN CALL ReportError(Mux%, "Could not open device Mux488")
RETURN

PreparePFG:
'  Bring the Programmable Function generator  on-line
   CALL IBDEV(0, PFG5105%, 0, T10s, 1, 0, PFG%)
   IF (PFG% < 0) THEN CALL ReportError(PFG%, "Could not open device PFG5105")

'  Set up PFG to generate DC signal, 4.99 volt and connect the output
   CALL IBWRT(PFG%, "DC 4.99")
   CALL IBWRT(PFG%, "OUTPUT ON")
   Txt$ = "Could not initialize PFG5105"
   IF (IBSTA% AND EERR) THEN CALL ReportError(PFG%, Txt$)
RETURN

PrepareDSA:      ' ------------- DSA 601 setting up ------------------
'  Bring the DSA 601 online
   CALL IBDEV(0, DSA601%, 0, T20s, 1, 0, DSA%)
   IF (DSA% < 0) THEN CALL ReportError(DSA%, "Could not open device DSA601")

'  Set up the DSA by reading the stored setting
'   CALL IBWRT(DSA%, "REC FPS8")         ' Recall Front panel setting #8
   CALL IBWRT(DSA%, "ENC MEAs:ASC")       ' Send data as ASCII encoding
   CALL IBWRT(DSA%, "select tra1")       ' Select trace 1
   Txt$ = "Could not initialize DSA"
   IF (IBSTA% AND EERR) THEN CALL ReportError(DSA%, Txt$)
RETURN

ReadCFG:
    PRINT "Reading the configuration file"
    NAvg% = 2: TimeDev = 1.5
    OPEN "das.cfg" FOR INPUT AS #1    ' Open the configuration file
    INPUT #1, Junk$, Junk$

INPUT #1, Junk$, CFGversion      ' configuration file version
    INPUT #1, Junk$, LocPath$        ' Local filepath
    INPUT #1, Junk$, NetPath$        ' Network filepath

    ' Set all GPIB addresses for all devices, and enable flag
    LINE INPUT #1, Junk$
    INPUT #1, DM5120%, DMMenabled        ' Voltmeter GPIB address
    LINE INPUT #1, Junk$
    INPUT #1, DSA601%, DSAenabled        ' DSA 601 GPIB address
    LINE INPUT #1, Junk$
    INPUT #1, Mux488%, MUXenabled        ' Multiplexer GPIB address

    ' Put these lines if you gonna use the High-Speed In-the-box
    ' averaging (thru 'bufave?' command)
    ' DMM setting
    'LINE INPUT #1, Junk$: INPUT #1, DMMbuf       ' DMM buffer size
    'LINE INPUT #1, Junk$: INPUT #1, StoInt       ' DMM storage interval

    ' Waveform assignments
    LINE INPUT #1, Junk$: PRINT Junk$    ' Waveform # for Cross measmnt
    IF INSTR(Junk$, "DSA") = 0 THEN PRINT "Wrong DAS.CFG format": STOP
    LINE INPUT #1, Junk$
    INPUT #1, DSAinput%
    LINE INPUT #1, Junk$
    LINE INPUT #1, Junk$
    FOR I = 1 TO DSAinput%
     INPUT #1, DSAchn(I), DSAtitle$(I), DSAmeasm$(I), DSAchnRemark$(I), DSAscrprn(I)
     PRINT DSAchn(I), DSAtitle$(I), DSAmeasm$(I), DSAchnRemark$(I)
    NEXT I
```

Figure C.8 Program Listing of DAS.BAS (Continued)

```
    ' Multiplexer input description
    LINE INPUT #1, Junk$: PRINT Junk$    ' Multiplexer description section
    IF INSTR(Junk$, "MUX") = 0 THEN PRINT "Wrong DAS.CFG format": STOP
    LINE INPUT #1, Junk$: INPUT #1, MuxInput%    ' Total MUX input
    LINE INPUT #1, Junk$: LINE INPUT #1, Junk$

    ' Description for all inputs
    FOR I = 1 TO MuxInput%
     INPUT #1, Chn(I), ChnTitle$(I), DMMfun$(I), DMMrng(I), ChnRem$(I), DMMscrprn(I)
     PRINT Chn(I), ChnTitle$(I), DMMfun$(I), DMMrng(I), ChnRem$(I), DMMscrprn(I)
    NEXT
    CLOSE #1
    'PRINT "LocPath$, Navg, DMMtime": PRINT LocPath$, NAvg%, DMMtime
RETURN

PrintCFGtoScreen:
    PRINT "Program parameters are: "
    PRINT "  Equipments: ";
    IF DMMenabled THEN PRINT "Voltmeter ";
    IF MUXenabled THEN PRINT "Multiplexer ";
    IF DSAenabled THEN PRINT "Oscilloscope ";
    PRINT
RETURN

OpenOutputFile:
' subroutine to prepare and open the output files (local and NFS)

Header1$ = "  Time   seconds "
Header2$ = Quot1$ + "Time" + Quot1$ + Quot2$ + "Elapsed" + Quot1$
Form1$ = "##### ":   Form2$ = "######.##, ######.#"
Form3$ = "#.####^^^^ ":  Form4$ = ", #.######^^^^"
FOR I = 1 TO DSAinput%
    Title1$ = LEFT$(DSAtitle$(I) + "           ", 10) + " "
    IF DSAscrprn(I) THEN Header1$ = Header1$ + Title1$

     Header2$ = Header2$ + Quot2$ + DSAtitle$(I) + Quot1$
NEXT

FOR I = 1 TO MuxInput%
    Title1$ = LEFT$(ChnTitle$(I) + "           ", 10) + " "
    IF DMMscrprn(I) THEN Header1$ = Header1$ + Title1$
    Header2$ = Header2$ + Quot2$ + ChnTitle$(I) + Quot1$
NEXT

' Open the output files
ThisTime = TIMER
File1$ = LocPath$ + DataFile$ + ".prn": DoThis$ = "del " + File1$
SHELL DoThis$                          ' Make sure no output file
OPEN File1$ FOR OUTPUT AS #1
PRINT #1, Quot1$; "Output of DAS.EXE, Data Acquisition System"; Quot1$
PRINT #1, Quot1$; "Date: "; DATE$, "Time: "; TIME$; Quot1$
PRINT #1, Quot1$; "Description: "; Junk$; Quot1$
PRINT #1, Quot1$; "Minutes between acquisition:"; AcqInt; Quot1$
PRINT #1, Header2$: CLOSE #1

'IF DumpWfm THEN          ' Dump the waveform header
'    FileWfm$ = LocPath$ + DataFile$ + ".hdr"
'    OPEN FileWfm$ FOR OUTPUT AS #1
'    CLOSE #1
'END IF

IF NFStoo$ = "" THEN NFStoo$ = "n"
NFStoo$ = UCASE$(NFStoo$)                  ' default save the file to network
Network = -1                               ' No NFS drive to save the file
IF NFStoo$ = "N" THEN Network   0

                                           ' Put the output on the network
IF Network THEN
   File2$ = NetPath$ + DataFile$ + ".prn": DoThis$ = "del " + File2$
   SHELL DoThis$                           ' Make sure no output file
```

Figure C.8 Program Listing of DAS.BAS (Continued)

```
   OPEN File2$ FOR OUTPUT AS #2
   PRINT #2, Quot1$; "Datafile from DM5120 Digital Voltmeter"; Quot1$
   PRINT #2, Quot1$; "Date: "; DATE$, "Time: "; TIME$; Quot1$
   PRINT #2, Quot1$; "Description: "; Junk$; Quot1$
   PRINT #2, Quot1$; "Minutes between acquisition:"; AcqInt; Quot1$
   PRINT #2, Header2$: CLOSE #2
END IF

RETURN

HelpScreen:
' subprogram to print help screen
' Selection is the code which section to print

Selection = 1
SELECT CASE Selection
    CASE 1
     PRINT
     PRINT "----- Keyboard Assignments ------------"
     PRINT
     PRINT "F1 : Help"
     PRINT "F2 : Program pause"
     PRINT "F3 : dump waveform to disket"
     PRINT "F4 : One-step mode / debug"
     PRINT "F9 : Print program configuration to screen"
     PRINT "F10 / ESC : Quit this program"
     PRINT


     CASE 2
     PRINT " Print program configuration here"
END SELECT
RETURN
' end of main program

SUB BogoMips (Sec, BogoIndex)
' subprogram to determine how fast a system is, by counting how many
' loops it can go for a certain time, defined in Mins.
' the output is BogoIndex
    StartTime = TIMER
    WHILE StartTime + Sec > TIMER
     BogoIndex = BogoIndex + 1
    WEND

END SUB

SUB CheckPID (Mode)
' subprogram to check PID (Process ID) file
' that will be used to determine whether another copy is running
' Mode=1 is for checking whether another copy is running
'       2 is for updating the PID file

File$ = "c:\dmm.pid"

IF Mode = 1 THEN
    PRINT "Checking PID file"
    DoThis$ = "dir c:\ > dmm.tmp": SHELL DoThis$    ' Make the directory listing
    OPEN "dmm.tmp" FOR INPUT AS #1                   ' Open the list
    WHILE NOT EOF(1)
     LINE INPUT #1, Junk$                           ' Scan for DMM.PID file
     IF INSTR(Junk$, "DMM") AND INSTR(Junk$, "PID") > 0 THEN Found = -1
    WEND: CLOSE #1

    ' We need to check whether the DMM.PID file that we just got
    ' is a stale file or not
    IF Found THEN
     OPEN File$ FOR INPUT AS #1
     INPUT #1, PIDTime
     IF PIDTime + 60 > TIMER THEN          ' this PID file is new
         BEEP: BEEP
```

Figure C.8 Program Listing of DAS.BAS (Continued)

```
        PRINT " ERROR!!!, Another copy of this file is running"
        DoThis$ = "del " + File$: SHELL DoThis$
        WHILE INKEY$ <> " ". WEND: END
     END IF
     CLOSE #1
    END IF
END IF

IF Mode = 2 THEN
    OPEN File$ FOR OUTPUT AS #1 ' Create/update the PID file
     PRINT #1, TIMER          ' with timestamp as the only content
     CLOSE #1
END IF

IF Mode = 3 THEN         ' Clear the PID file at the end of execution
    DoThis$ = "del " + File$: SHELL DoThis$
END IF

END SUB

SUB FirstArrival (Ident%, Stream%, Mode%, Zero!)
'
' subprogram to determine time of the first arrival, by analyzing
' the whole waveform
' by James Davidson

' Ident% is the numeric identifier of the GPIB device
' Stream% is the waveform number
' Mode% is the mode of operation
'       1 means acquire the heading data
'       2 means acquire the waveform and find the first arrvial
'       3 means acquire the wfm and save it to a file
'         in this case Zero! is the numeric serial # for the file
' Reading! is the time (in seconds) of the first arrival

SHARED Network, LocPath$, DataFile$
'SHARED Xincr, Xzero, Nstrt%, Nend%, Hurd, Nfit
'PRINT "CFG file check": PRINT XIncr, Xzero, Nstrt%, Nend%, Hurd, Nfit: STOP
N = 5

DIM Wfm(1 TO 1024), awfm(1 TO 1024), X(1 TO N), Y(1 TO N)

    IF Stream% = 0 THEN PRINT "No waveform selected!!!": STOP
    IF Mode% = 0 THEN PRINT "No mode of operation selected!!!": STOP

    IF Mode% = 1 THEN                    ' Get the XINCr and XZERO
     NAvg% = 1
     CALL UseDSA(Ident%, "WFM? XIncr", NAvg%, Stream%, Xincr)
     CALL UseDSA(Ident%, "WFM? XZEr", NAvg%, Stream%, Xzero)
    END IF

    IF Mode% = 2 OR Mode% = 3 THEN                ' Download the waveform
     Trace$ = "select tra" + LTRIM$(STR$(Stream%))
     Trace2$ = "output tra" + LTRIM$(STR$(Stream%))
     CALL IBWRT(Ident%, Trace$)           ' Select the particular trace
     CALL IBWRT(Ident%, Trace2$)
     Txt$ = "Could not select waveform on the DSA 601"
     IF (IBSTA% AND EERR) THEN CALL ReportError(Ident%, Txt$)

     Junk$ = SPACE$(9800)
     CALL IBWRT(Ident%, "CURV?")
     CALL IBRD(Ident%, Junk$)        ' this junk$ is an array of 1024 numbers
     SpcLoc = INSTR(Junk$, " ")
     Junk$ = MID$(Junk$, SpcLoc + 1)
     OPEN "tmp" FOR OUTPUT AS #4     ' Save into temporary file
         PRINT #4, Junk$
     CLOSE #4
    END IF
```

Figure C.8 Program Listing of DAS.BAS (Continued)

```
    IF Mode% = 2 THEN
     PRINT "This least square method for first arrival determination"
     PRINT "is already disabled"
     WHILE INKEY$ = "": WEND: END
    END IF

    IF Mode% = 3 THEN    ' Acquire and download the waveform
     Numer$ = LTRIM$(RTRIM$(STR$(Zero!)))            ' Convert to character
     LocFile$ = LocPath$ + DataFile$ + "." + Numer$
     NetFile$ = NetPath$ + DataFile$ + "." + Numer$
     PRINT "Dumping a waveform ("; LocFile$; ") to a file"
     OPEN "tmp" FOR INPUT AS #4       ' Open the temporary file
     OPEN LocFile$ FOR OUTPUT AS #5   ' Open the output files
     IF Network THEN OPEN NetFile$ FOR OUTPUT AS #6

     FOR I = 1 TO 1024                ' read all numbers
         INPUT #4, Wfm(I)
         PRINT #5, Wfm(I): IF Network THEN PRINT #6, Wfm(I)
      NEXT: CLOSE #4: CLOSE #5: IF Network THEN CLOSE #6
    END IF

END SUB

SUB ReportError (fd%, errmsg$) STATIC

   PRINT "Error = ", IBERR%; errmsg$
   IF (fd% <> -1) THEN
      PRINT ("Cleanup: taking board off-line")
      CALL IBONL(fd%, 0)
   END IF
   WHILE INKEY$ = "": WEND
   'STOP                          ' Abort program
   END

END SUB

SUB SumAvg (Mode, NData, Value, NewValue)
' subprogram todo averaging
' if mode=1 summing up
'       adding Value to NewValue, and increment Ndata
' mode=2 divide the sum for the average value
'       divide Value by Ndata and put the result on NewValue

    IF Mode = 0 THEN PRINT "Averaging mode=0 !": STOP
    IF Mode = 1 THEN
     NewValue = NewValue + Value
     NData = NData + 1
    END IF
    IF Mode = 2 THEN
     NewValue = Value / NData         ' Average
     Value = 0                        ' Reset the summation
     NData = 0                        ' Reset the counter
    END IF
END SUB

SUB UseDMM (Ident%, Mode%, DMMfun$, DMMrng, BufSize%, StoInt%, DCV)
'
' subprogram to control the DM5120 Digital Voltmeter
' Ident% is the numeric identifier for this particular GPIB device
' Mode% is the mode of the subprogram
' DMMmode$ is the mode of measurement of the DMM
' DMMrng is the measurement range the DMM
' BufSize% is the buffer size
' StoInt% is storage to buffer interval (ms)
' DCV is the DC voltage reading (or any voltage reading set on the panel)

IF Mode% = 0 THEN PRINT "No mode is selected": STOP
'IF DMMmode$ = "" THEN PRINT "No measurement mode is selected": STOP
IF Ident% = 0 THEN PRINT "No device (Ident%) is selected": STOP
'IF Range% < 1 OR Range% > 7 THEN PRINT "DMM range selection is out of range": STOP
```

Figure C.8 Program Listing of DAS.BAS (Continued)

```
' convert DMMrng to it's integer code
Range% = 0
IF DMMrng = 300 THEN Range% = 4
IF DMMrng = 30 THEN Range% = 3
IF DMMrng = 3 THEN Range% = 2
IF DMMrng = .3 THEN Range% = 1

    IF Mode% = 1 THEN                       ' Reset the DMM
     CALL IBWRT(Ident%, "trigger ext,cont")
     CALL IBWRT(Ident%, "dt trig")
     CALL IBWRT(Ident%, "digit 3")
     CALL IBWRT(Ident%, "delay 100")
     CALL IBWRT(Ident%, "datfor off")
     IF BufSize% = 0 AND StoInt% = 0 THEN CALL IBWRT(Ident%, "digit 6")
    END IF

     IF Mode% = 2 THEN                      ' set the DMM parameters and trigger

     ' set the DMM according to the measurement params
     SetDMM$ = "range" + STR$(Range%): CALL IBWRT(Ident%, SetDMM$)
     SetDMM$ = "bufsz" + STR$(BufSize%): CALL IBWRT(Ident%, SetDMM$)
     SetDMM$ = "stoint" + STR$(StoInt%): CALL IBWRT(Ident%, SetDMM$)

     CALL IBTRG(Ident%)                 ' trigger the DMM
     Txt$ = "Could not trigger multimeter"
     IF (IBSTA% AND EERR) THEN CALL ReportError(Ident%, Txt$)
    END IF

    IF Mode% = 3 THEN                       ' Measure the input at DMM
     ' Change the function
     SetDMM$ = "FUNCT " + DMMfun$: CALL IBWRT(Ident%, SetDMM$)

     ' change the range
     SetDMM$ = "range" + STR$(Range%): CALL IBWRT(Ident%, SetDMM$)

     ' Read the asked value in the buffer
     CALL IBWRT(Ident%, "READ ADC")
     Txt$ = "Could not trigger multimeter"
     IF (IBSTA% AND EERR) THEN CALL ReportError(Ident%, Txt$)

     ' Read data from DMM
     Reading$ = SPACE$(20): CALL IBRD(Ident%, Reading$)
     Txt$ = "Could not read data from multimeter"
     IF (IBSTA% AND EERR) THEN CALL ReportError(Ident%, Txt$)

     RD$ = LEFT$(Reading$, IBCNT%): BlnkLoc = INSTR(RD$, " ")
     SemColLoc = INSTR(RD$, ";")
     DCV = VAL(LEFT$(RD$, SemColLoc - 1))
     'PRINT RD$, DCV
    END IF

END SUB

SUB UseDSA (Ident%, Param$, NAvg%, Stream%, ParamValue)
'
' subprogram to query the DSA 601 for Cross Measurement time
' Ident% is the numeric identifier for this particular GPIB device

IF Stream% = 0 THEN PRINT "No waveform selected!!!": STOP
IF Ident% = 0 THEN PRINT "No device selected!!!": STOP

OutputFormat = 1                    ' the regular output
IF INSTR(UCASE$(Param$), "WFM") > 0 THEN OutputFormat = 2    ' for WFM output

    Trace$ = "select tra" + LTRIM$(STR$(Stream%))
    CALL IBWRT(Ident%, Trace$)              ' Select the particular trace
    Txt$ = "Could not select waveform on the DSA 601"
    IF (IBSTA% AND EERR) THEN CALL ReportError(Ident%, Txt$)
```

Figure C.8 Program Listing of DAS.BAS (Continued)

```
    FOR j = 1 TO NAvg%
    ' Request for Param$ measurement time reading
      CALL IBWRT(Ident%, Param$)
      Txt$ = "Could not trigger the DSA 601"
      IF (IBSTA% AND EERR) THEN CALL ReportError(Ident%, Txt$)

    ' Read data from DSA
      Reading$ = SPACE$(30): CALL IBRD(Ident%, Reading$)
      Txt$ = "Could not read data from the DSA"
      IF (IBSTA% AND EERR) THEN CALL ReportError(Ident%, Txt$)

    ' Remove blank spaces in READING$ and assign resulting buffer to RD$.
      RD$ = LEFT$(Reading$, IBCNT%)

    ' Convert to a numeric variable
    IF OutputFormat = 1 THEN
      ParLen = LEN(Param$): ComLoc = INSTR(RD$, ",")
      ParamValue = VAL(MID$(RD$, ParLen + 1, ComLoc - 1))
    END IF
    IF OutputFormat = 2 THEN
        PRINT RD$
        ColLoc = INSTR(RD$, ":")       ' colon position
        ParamValue   VAL(MID$(RD$, ColLoc + 1))
    END IF

    SumValue = SumValue + ParamValue
   NEXT

   'Average the time reading out of Navg readings
   ParamValue = SumValue / NAvg%

END SUB

SUB UseMux (Ident%, Mode%, Stream%, QueryBack$)
'
' subprogram to control the Mux488 Multiplexer box
' Ident% is the device identifier
' Mode% is the subprogram op mode
'       1 for resetting the box
'       2 for switching inputs
' Stream% is the channel input number
' QueryBack$ is the response back from the multiplexer box

    IF Mode% = 1 THEN
     PRINT "Resetting the Mux";
     DoThis$ = "C1X": CALL IBWRT(Ident%, DoThis$)
     'FOR I = 1 TO 500: FOR j = 1 TO 1000: NEXT: NEXT: BEEP
     PRINT "  - Done "
     DoThis$ = "C?X": CALL IBWRT(Ident%, DoThis$)
     Reading$ = SPACE$(30). CALL IBRD(Ident%, Reading$)
     Txt$ = "Could not read data from the Mux488"
     IF (IBSTA% AND EERR) THEN CALL ReportError(Ident%, Txt$)
     QueryBack$ = LEFT$(Reading$, 6)
     'PRINT QueryBack$: STOP
    END IF

    IF Mode% = 2 THEN
     ' change the input channel
     Chan$ = LTRIM$(RTRIM$(STR$(Stream%)))
     DoThis$ = "C" + Chan$ + " X": CALL IBWRT(Ident%, DoThis$)

     ' Readback the input channel, for a confirmation
     DoThis$ = "C? X": CALL IBWRT(Ident%, DoThis$)
     Reading$ = SPACE$(10): CALL IBRD(Ident%, Reading$)

     Txt$ = "Could not read data from the Mux488"
     IF (IBSTA% AND EERR) THEN CALL ReportError(Ident%, Txt$)
     QueryBack$ = LEFT$(Reading$, 10)
    END IF

END SUB
```

Figure C.8 Program Listing of DAS.BAS (Continued)

```
SUB UsePFG (Ident%, Txt1$, Txt2$)
'
' subprogram to control the PFG 5105 Signal generator
' Ident% is the instrument identifier
' Txt1$ is the command to the PFG
' Txt2$ is the output string from the PFG
'
      ' Give command to the PFG
        CALL IBWRT(Ident%, Txt1$)
        Txt$ = "Could not trigger PFG"
        IF (IBSTA% AND EERR) THEN CALL ReportError(Ident%, Txt$)

END SUB
```

Figure C.8 Program Listing of DAS.BAS (Continued)

```
'
'       BALANCE . BAS
'
' AND model FR-300 MK-II in Command Mode
'
' Paulus S. Adisoemarta (May 30, 1996)
' June 1, 1996 (finally work ok)
'
' Variables preparation
DQ$ = CHR$(34)                                          ' Double quote (")
CM$ = CHR$(44)                                          ' Command (,)
OneDay = 86400                                          ' Total seconds in a day

CLS
' Balance preparation
     PRINT "Resetting the balance"
     OPEN "COM1-9600,,,,CS" FOR RANDOM AS #1                        ' Open the device I/O port
     'PRINT #1, "OFF" + CHRS(13). FOR I = 1 TO 10000: NEXT
     'PRINT #1, "ON" + CHR$(13): FOR I = 1 TO 500000: NEXT

     'PRINT #I, "CK" + TIMES + CHR$(13)                         ' reset the clock at balance
     'FOR I = 1 TO 1000: FOR J = 1 TO 100: NEXT: NEXT

     PRINT #1, "R" + CHR$(13)
     LINE INPUT #1, AK$' reply to "R" command (ReZero command)
     IF AK$ <> CHR$(G) THEN PRINT '*Balance not Ready!"· CLOSE : END

     LINE INPUT #1, AK$' end of ReZero
     IF AK$ = "EC,EO" THEN PRINT "Communcation Error!": CLOSE   END
     IF AK$ = "EC,E11" THEN PRINT "Error 1 . . . Balance not Stable": CLOSE : END

' Output file preparation
     INPUT "Output filename, no extention "; FileN$
     INPUT "Sample description "; SampDescr$
     INPUT "Data reading interval, seconds "; ReadInt
     INPUT "Interval multiplier, [1-1.2]   "; IntMul
     INPUT "Use int. mult after, mins      "; UseMultMin

     OutFn$ = FileN$ + ".bal"' Output filename
     DbgFn$ = FileN$ + ".dbg"' debug output file

     OPEN OutFn$ FOR OUTPUT AS #2
     PRINT #2, DQ$; "Balance output from AND modem FR300 balance": DQ$
     PRINT #2, DQ$; DATES; " , "; TIMES; DQ$
     PRINT #2, DQ$; "Sample description : "; SampDescr$* DQ$
     PRINT #2, DQ$; " Read interval · "; ReadInt; I;Qs
     PRINT #2, DQ$; " Interval multiplier : "; IntMul; DQ$
     PRINT #2, DQ$; " Use interval multiplier after · "; UseMultMin; " min"; DQ$

     OPEN DbgFn$ FOR OUTPUT AS #3
     PRINT #3, "Debug output from AND balance"
     PRINT #3, DATES; " , "; TIMES
     PRINT #3, "Sample description : "; SampDescr$

     INPUT "Press ENTER to start acquisition"; Junk$

Acquire = -1: First = -1                                ' Flags
StartTime = TIMER                                       ' Note the starting time
LastTime = TIMER                                        ' to avoid big elapsed number

WHILE Acquire                                           ' The MAIN loop
     Elapsed= TIMER StartTime                           ' Total seconds run time

     IF Day > 0 THEN Elapsed = Elapsed + Day * OneDay
     IntVal = TIMER   LastTime                          ' Elapse since last reading
     IF IntVal < 0 THEN                                 ' Negative means just pass
          First = -1                                    ' midnight force a reading
          Day = Day + 1                                 ' add one day
     END IF
```

Figure C.9 Program Listing of BALANCE.BAS

```
    IF IntVal > ReadInt OR First THEN
         LastTime = TIMER: First = 0                              ' Note measurement time
         IF IntVal < 0 THEN IntVal = IntVal + OneDay                      ' for midnight pass

         GOSUB GetFive                                            ' get current value
         PRINT TIMES, TIMER, IntVal, AvgReading' print to screen and file
         PRINT #2, DQ$; TIMES; DQ$; CM$, TIMER; CM$, IntVal; CM$, AvgReading
         IF Elapsed > UseMultMin * 60 THEN                        ' Use increasing interval ?
              ReadInt= ReadInt * IntMul                           ' increase interval time
         END IF
    END IF


    K$ = INKEY$
    IF LOF(I) > 255 AND K$ = CHR$(27) THEN                        ' if ESC key pressed
         SOUND 665, 4: SOUND 330, 3                               ' then exit gracefully
         Acquire = 0
    END IF

WEND                                                              ' end of the MAIN loop
PRINT *''End of measurementsrf: CLOSE : END

GetFive:
' Subroutine to get five consecutive reading
     Sum = 0                                                      ' reset the accumulator
     FOR K = 1 TO 5                                               ' Loop five times
          GOSUB GetOne                                            ' get a reading
          Sum = Sum + Wt                                          ' sum it up
          FOR L = 1 TO 10000: NEXT                                ' just to slow it down
     NEXT
     AvgReading = Sum / 5                                         ' the average value
     RETURN

GetOne:          ' Subroutine to get one good number, discard the bad one
Query:
     PRINT #1,"Q" f CHR$(13)                                      ' send "Q" to the balance
     INPUT #1, HD$, DT$                                           ' read the response back
     PRINT #3, DATES; " -"; TIMES, HD$, DT$
     IF HD$ ="EC" THEN                                            ' it has error then repeat
          'PRINT HD$, DT$
          FOR I = 1 TO 100: FOR J = 1 TO 500: NEXT: NEXT' wait a while
          GOTO Query' go back to get another reading
     END IF
     BlnkLoc = INSTR(DT$, " ")                                    ' find the blank after the number
     Wt = VAL(LEFT$(DT$, BlnkLoc))                                ' parse and convert the reading
RETURN
```

Figure C.9 Program Listing of BALANCE.BAS (Continued)